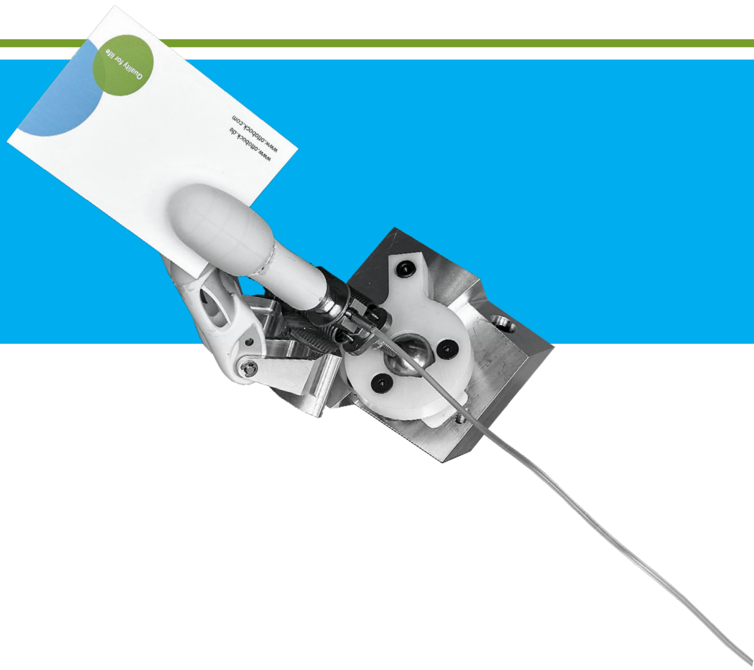
Developing a Body-Powered Co-Contraction Equivalent

Applied to switch between a lateral and an opposition grip



by Sarah Bierbaum

Quality for life

Developing a Body-Powered Co-Contraction Equivalent

Applied to Switch Between a Lateral and an Opposition Grip

by

Sarah Bierbaum

in cooperation with Otto Bock HealthCare GmbH

in partial fulfillment of the requirements for the degree of

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Student number:	4414039	
Supervisor:	Dr. ir. D. H. Plettenburg	
Company Supervisors:	T. Bertels,	
	L. Brünjes	
Thesis committee:	Prof. dr. F. C. T. van der Helm,	TU Delft
	Dr. ir. D. H. Plettenburg,	TU Delft
	Dr. ir. M. Langelaar,	TU Delft
	Dr. ir. J. F. L. Goosen,	TU Delft
	T. Bertels,	Otto Bock HealthCare GmbH

Preface

In this master's thesis I will introduce a body-powered co-contraction equivalent – a mechanism, which enables to switch between a lateral and an opposition grip of a body-powered prosthesis as easily as with the myoelectric co-contraction. The project was conducted in cooperation with Otto Bock HealthCare GmbH in Duderstadt, Germany, and represents the culmination of my degree of Master of Science in Biomedical Engineering at the TU Delft.

The idea to implement multiple degrees of freedom in a body-powered prosthesis arose from Otto Bock's consideration to develop a body-powered alternative to their advanced myoelectric Michelangelo Hand. Thus, this work began with an extensive literature study which investigated "Mechanisms to control and alter multiple degrees of freedom of body-powered hand prostheses". From this literature study, the following concrete task emerged: "Develop a mechanism, with which a user of a body-powered prosthesis can easily select between a lateral and an opposition grip". This report will include a detailed description of the mechanism that was developed, the design process, as well as the literature review which preceded this thesis work. Accordingly, the report is divided into three chapters:

1. **Scientific Paper**: This chapter is considered to be the main element of this thesis. It is written in the form of a scientific paper and presents the results of the final version of the manufactured model.
2. **Detailed Design Process**: This chapter describes the design process and the analysis of the model in more detail. For example, the specific design methods applied, the steps of iteration conducted in this project, or the calculations that were made to estimate the model's mechanical properties are presented. This chapter is written in such a way that it can be read independently from the scientific paper. Hence, paragraphs of the scientific paper are incorporated in this chapter.
3. **Literature Review**: This chapter comprises the literature review which preceded the thesis, investigating "Mechanism to control and alter multiple degrees of freedom of body-powered hand prostheses".

Furthermore, data sheets of the springs used in the manufactured model as well as technical drawings of the model components are included in the Appendix of this report. However, information regarding components taken from the Michelangelo Hand cannot be made public and hence, are not shown or dimensioned in the technical drawings.

Acknowledgments

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- first of all Lukas Brünjes & Thomas Bertels, my supervisors at Otto Bock, for sharing their expertise, giving new food for thoughts, revealing some ideas and their opinions, and for generally improving my skills as an engineer. I could approach you at any time regarding any questions, doubts or problems; thank you for being such great supervisors and colleagues!
- Dick Plettenburg, my academic supervisor from the TU Delft, for providing continuous feedback and helpful advice despite the distance between Duderstadt and Delft.
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Thank you all very much! I really enjoyed working on this project!

Finally, I must express my deep gratitude to my parents and to my sister for their patience and encouragement, as well as for their support and unconditional love throughout my studies. Thank you for listening to my worries at any time of the day, for celebrating my successes and especially for always believing in me.

Sarah Bierbaum
Göttingen, March 2017

Statement of Authorship

I hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged.

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This master thesis is based on internal, confidential data and information of the company *Otto Bock HealthCare GmbH*.
This work may only be available to the first and second reviewers and authorized members of the board of examiners. Any publication and duplication of this final thesis as well as passing on of information from the thesis - even in part - is prohibited until November 25th, 2021.
An inspection of this work by third parties requires the expressed admission of the author and the company.

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Acronyms

CAD computer-aided design

CMC carpometacarpal joint

DoFs degrees of freedom

IP interphalangeal joint

MCP metacarpophalangeal joint

VC voluntary-closing

VO voluntary-opening

VO/VC-devices voluntary-opening & voluntary closing devices

TD terminal device

I

Scientific Paper

A Body-Powered Co-Contraction Equivalent To Switch the Grip Type

Sarah Bierbaum

Abstract—Body-powered and myoelectric prostheses have both their specific advantages. Body-powered prostheses are e.g lightweight, robust, cheap and provide extended proprioceptive feedback. Myoelectric devices on the contrary facilitate multiple degrees of freedom, which are controlled simply by e.g. co-contraction or a specific trigger signal. In order to expand the advantages of body-powered prostheses with the myoelectric feature of multiple degrees of freedom, the aim of this project was to develop a mechanism to operate multiple degrees of freedom of a body-powered prosthesis as easily as the myoelectric control. More precisely, the mechanism should enable the switch between a lateral and an opposition grip of a body-powered hand prosthesis. In this regard, a mechanism was developed for a voluntary opening hand, in which one control cable is responsible for both the opening of the hand and the switch of the grip type. Initially, the force applied to the control cable causes the opening of the hand. When the hand is fully opened, additional force exerted on the control cable changes the grip type. The mechanism is based on a thumb guiding pin, which moves within a parabolic-shaped pathway. Each pathway branch represents one of the grip types. Consequently, a change of the grip type results from the thumb guiding pin switching the pathway branch. Since a model was manufactured, which proves the functionality of this concept in practice, the design goal of this project was achieved.

Index Terms—Body-Powered Prosthesis, Lateral Grip, Multiple Degrees of Freedom, Opposition Grip, Prosthetic Design, Prosthetic Hand, Switch of Grip Type, Voluntary Opening.

1 Introduction

Hand prostheses are currently commercially available as myoelectric or body-powered devices. Myoelectric prostheses are controlled by muscle signals recorded from antagonistic muscles and actuated by electrical motors, which drive motions like hand opening, hand closing, switching of the grasp type or wrist movements. In contrast, body-powered prostheses are controlled and actuated predominantely by motions of the residual limb and the contralateral shoulder. A Bowden cable connects the prosthetic terminal device (TD) to a harness worn by the amputee. Hence, it couples the amputee's body motion to TD opening or closing. Due to cables solely being capable of transferring tension, the reversed prehension movement is conducted by means of passive elements [1].

Both prosthetic types have their specific advantages. Myoelectric prostheses for example have the characteristic of facilitating multiple degrees of freedom (DoFs) due to changes in the grip pattern in form of a positionable thumb, independently movable fingers and/or due to wrist movements. In short explained, with a high advanced myoelectric prostheses the amputees can select between different grasp patterns or activate wrist rotation by co-contracting the muscles, giving a special trigger signal or applying a signal combination. The independently movable and adapting fingers lead to a more stable grip especially in case of irregularly shaped objects. Furthermore, the implementation of multiple DoFs lead to a more natural appearance of the prosthetic usage as well as to an improvement in functionality, accuracy of grasping and dexterity in conducting complex movements in everyday life [2]. Moreover, prostheses with multiple DoFs also reduce the need for compensatory body movements compared to prosthetic devices with only one DoF and hence, lower the occurance of physical long-term damages [3], [4]. In contrast to the advanced myoelectric prosthetic hands, body-powered ones only promote active opening or closing. However, body-powered prostheses also have significant advantages over myoelectric ones: they are lightweight, robust, cheap and independent of external energy. Furthermore, body-powered prostheses facilitate extended proprioceptive feedback, whereby the amputee knows the prehension state (opened or closed) of the TD, its position and the applied amount of force without having to visually monitor the activity of the hand [1]. This tremendously reduces the mental load of the body-powered prosthesis usage.

Motivated by the advantages of body-powered prostheses, in particular the extended proprioceptive feedback, the company *Otto Bock HealthCare GmbH*, Duderstadt, considers to integrate the benefits of the advanced myoelectric Michelangelo Hand (*Otto Bock HealthCare Products GmbH*, Vienna) in a body-powered prosthesis. The features of the Michelangelo Hand are an actively positionable thumb and adaptive fingers [5]. For this, the myoelectric hand comprises two motors: one responsible for flexing

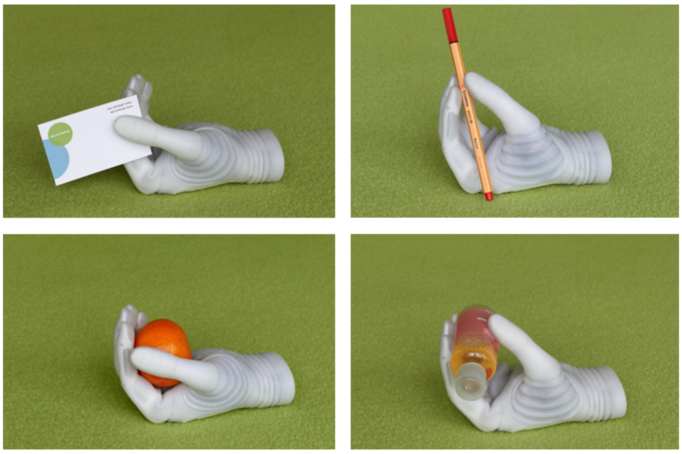


Fig. 1: Grip Types of the Michelangelo Hand: lateral pinch grip (top, left), lateral power grip (bottom, left), opposition pinch grip (top, right) & opposition power grip (bottom, right).

the fingers and the thumb and the other motor to change the thumb position. By e.g. co-contracting the amputee can switch between the thumb approaching the index finger laterally (lateral grip) or opposing index and middle finger (opposition grip) (Figure 1, columns). Due to the adaptive fingers two variations are achieved in both grip types: the pinch grip to promote sensitivity and dexterity and the power grip to ensure security and stability [6] (see Figure 1, rows). In the Michelangelo Hand the adaptive fingers and hence, the switch between pinch and power grip are realized by means of differential coupling of the index and the middle finger. The ring and the little finger are passively dragged along.

Regarding the implementation of these features of the Michelangelo Hand in body-powered prostheses current research focuses on the realization of pinch and power grips to ensure stable and dexterous handling of objects, independent of their size and shape. The idea of realizing adaptive fingers by using differential coupling is named underactuated hands. The body-powered underactutated prototypes, described in literature, present interesting potential solutions how the finger mechanism in a body-powered Michelangelo Hand could be implemented. However, so far the implementation of an actively positionable thumb has not been approached in a body-powered prostheses. This, though, is an important feature since the thumb contributes to at least 40 % of the hand functionality [7]. Furthermore, measurements regarding how often Michelangelo Hand users apply a lateral or an opposition grip revealed that a lateral grip is with around 75 % more frequently employed than an opposition grip [2]. This reflects the significance of equipping body-powered hand prostheses with an actively positionable thumb since currently commercially available body-powered hands solely promote an opposition grip. Therefore, specifically the design of an actively positionable thumb for a body-powered prosthesis is addressed in this paper.

An extensive literature review has shown, that less successful attempts have already been conducted on this regard. The characteristic of a positionable thumb was mostly implemented in body-powered prostheses by either varying the thumb position using the sound hand or by operating an additional cable. However, these approaches are mentally challenging, counterintuitive or restricted to unilateral amputees. Hence, they are inadequate solutions especially compared to the simple control of multiple DoFs in myolectric prostheses.
In order to expand the advantages of body-powered prostheses, it is desirable to have a similar simple and little mentally challenging solution as the myoelectric control to change the grip type: **a body-powered co-contraction equivalent to switch the grip type**. Consequently, the aim of this project was to develop a mechanism, which enables the amputee to switch between a lateral and an opposition grip of a body-powered prosthesis as easily as with the myoelectric co-contraction. The funcionality of the developed mechanism should be proven by means of a functional model.

In the first part of this paper the design process starting with the design requirements of such a body-powered co-contraction equivalent up to the final manufactured model is presented. In the second part the functionality of the model is discussed and further improvements for the design suggested. Lastly, a conceptual solution for the finger mechanism is outlined since this is the next major step to design a complete body-powered Michelangelo Hand.

2 Methods

Deduced from the research goal to design a body-powered co-contraction equivalent, which enables to switch between a lateral as well as an opposition grip, the mechanism needs to promote two characteristics: a secure selection of a mode and the control of the chosen mode in an active manner.
To ensure a target-oriented development, requirements for the design were elaborated. Moreover, they were classified as “must”-, “should”- or “could”-requirements illustrating the importance of the criteria to be implemented in the final design. Based on these rated specifications conceptual solutions were elaborated and evaluated to identify the most promising one.
The requirements for the body-powered co-contraction equivalent can be broadly categorized as referring to the function, the control, the user group, the comfort, the appearance, the costs and

the transferability of the mechanism to be designed. These categories and the concretely elaborated requirements are further elucidated in the following.

2.1 Requirements

1) **Function**: The mechanism must promote switching between a lateral and an opposition grip. During the change of the grip type the thumb motion should appear natural. Because of Otto Bock's Michelangelo Hand serving as a model for the final hand design, the thumb positions achieved with the designed mechanism should match the thumb positions of the Michelangelo Hand for the corresponding grip within a limit of $\pm 5°$.
Commercially available body-powered prostheses can solely promote either active hand opening or hand closing. Depending on which prehension movement the device supports, it is characterized as voluntary opening (VO) or voluntary closing (VC). In case of a VO prosthesis the amputee opens the hand by tensioning the control cable. As soon as the force acting on the cable is released, hand closing is conducted passively by means of supporting elements such as springs or elastics. VC devices work vice versa [1]. Comparable to commercially available prostheses the mechanism must either be VO or VC; ideally, it could support both prehension movements simultaneously or a switch between both modes and hence enable a two-way control.
To ensure usability of the hand in everyday life, the opening width of the design should reach at least 80 mm, so that a large variety of objects (e.g. a paper cup or a water battle) is graspable. The defined maximum opening width is comparable to the ones of commercially available VO hands, which range from 67 mm to 85 mm [8]. To not only be able to wrap the designed device around these objects, but to actually be able to manipulate them, a grip force of at least 20 N should be achievable in both grip types [8], [9].

2) **Control**: Since the goal of this project is to design a body-powered prosthesis, the mechanism must be controlled and activated by body motion(s). The device should be operated with a harness - ideally it could be controlled with Otto Bock's standard harness *21A36=1* for below-elbow amputees. If the harness design needs to be adapted, e.g. by adding an additional control cable, changes to the harness should prevent the user and his/her clothes from any damages.

3) **User group**: Unilateral, below-elbow amputees must be capable to operate the mechanism. Consequently, the maximum control force required to manipulate the mechanism should be below 140 N, as derived from measurements conducted by C. L. Taylor [10]. He has revealed, that healthy subjects can apply on average a maximum control force of 280 N by means of arm flexion, which is the common body motion below-elbow amputees apply to operate their device [8], [9], [10]. Because of children with congenital defects only being capable of achieving a force, which 1.5-2.0 times lower than the maximum force a healthy child can exert, a similar ratio is assumed for an amputee compared to a healthy subject [11]. Thus, the maximum force to activate the designed mechanism was set to 140 N. The control forces of the ungloved body-powered hooks and hands studied by Smit et al. [8], [9] generally also do not exceed this value. Based on C. L. Taylor's study, the cable excursion should not exceed 53 mm [10].
Ideally, the mechanism could also be operated by bilateral or above-elbow amputees.

4) **Comfort**: The usage of the mechanism should be comfortable. Accordingly, the mechanism should have a low mass of less than 207 g. This magnitude equals the mass of the two motors of the Michelangelo Hand, which will be replaced by the designed mechanism.
The usage of the mechanism should be as little fatiguing as possible. Therefore, in case of a constant control motion being required to operate the mechanism, the permanently applied force should be less than the critical force of 25.2 N. The critical force describes the force level which can be applied for a prolonged time period without fatigue. It equals around 18% of the maximum force value. With the maximum control force set to 140 N the limit of 25.2 N for a permanently applied force is derived [9], [12].
Having changed the grip type, the device must be usable without readjustment of the harness. Moreover, the initial displacements of the control cable in both grip types should only deviate up to 4 mm.
Lastly, the usage of the mechanism could be intuitive and as little mentally challenging as possible [1].

1. The design specifications of "being intuitive" and "little mentally challenging" should generally be a "should"- rather than a "could"-requirement. However, due to these characteristics being difficult to evaluate in an objective way, it was decided to implement the two criteria as a "could"-requirement in this thesis.

5) **Appearance**: The mechanism should be visually and acoustically inconspicuous. Hence, the mechanism should not add a height of more than 18 mm to the size of a common body-powered prosthesis. This value corresponds to the height batteries used to project from the first generation of myoelectric prostheses. Furthermore, the acoustic level of the working mechanism should be below 35 dB, which is defined as a comfortable acoustic level [13].

6) **Costs**: An adequate sales price was devised with Otto Bock's product management specialized in upper-limb prosthetics. Derived from the estimated sales price, the maximum manufacturing costs should be less than €75.

7) **Robustness**: The mechanism should be durable for at least five years. Consequently, the device should survive 500,000 testing cycles of switching the grip type and grasping with the maximally achievable pinch force.
Furthermore, the mechanism should be resistant to temperatures between -20°C and +60°C.

8) **Transferability**: Ideally, the mechanism could be applied to switch between other movements (e.g. wrist pronation/supination and gripping).

In addition to the requirements stated before, the prosthetic device should be waterproof and dirt-repellent. Due to these features actually being a characteristic of the cosmesis rather than the mechanic, these latter requirements will not be considered in this project.

2.2 Design Approach

To get inspired regarding potential solutions for a body-power co-contraction equivalent, mechanisms of body-powered devices such as VC locks, two way-controlled prosthetic hands, hooks with altering maximum grip strengths and prosthetic elbows, which already comprise either a switching or a locking mechanism, were studied. Moreover, switching mechanisms beyond the field of prosthetics such as an old pull switch for lights, a ballpoint pen or railway switches, were examined to find further suitable solutions for the design goal. Brainstorming and the construction of a morphological scheme revealed that the mechanism could be realized in very diverse ways.
To narrow the numbers of possibilities, additional determinations were discussed with experts in the field of body-powered upper-limb prostheses at Otto Bock. Furthermore, a specialist in patient care with body-powered prostheses at Otto Bock, was interviewed in order to include the view of the prosthesis user also in the design process. Owing to the conversation with the experts, the following determinations were elaborated:

- Design a purely mechanical system due to the company's expertise in developing and manufacturing purely mechanical body-powered prostheses. Furthermore, in this way all body-powered characteristics can be ensured.
- Discard the idea of sensors to keep the amputee within the control cycle.
- Keep the control of the mechanism similar to the current principle since patients, accustomed to the current one, will hardly adapt to a completely new control mechanism; ideally use the existing control cable to change between a lateral and an opposition grip.

Step-by-step the idea emerged to trigger the switching of the grip type by an overloading principle: when a VO hand is fully opened, additional force applied to the control cable will initiate the change of grip type.

Conceptual solutions based on this principle were developed and evaluated with regard to the design requirements. Herein the "Weighted-Objectives"-method was applied, by which the following concept was identified to have the highest potential for further elaboration.

2.3 Conceptual Solution

The chosen concept is illustrated in Figure 2. In the following, a switching from the lateral grip (drawn in Figure 2) to the opposition grip will be depicted:

- The control force (red) applied to the thumb dummy (yellow) causes movement of the thumb dummy towards the pathway apex and hence, opening of the hand.
- Since the thumb dummy was initially located in its lateral grip position, the thumb dummy is moved within the lateral pathway branch (orange) towards the pathway apex. The pathway apex corresponds to the thumb position during an open-palm grip, in which the hand is maximally opened and the thumb lies in the palmar plane fully abducted in radial direction.
- The retraction spring is tensioned in correlation to the movement of the thumb dummy towards the pathway apex and consequently, in correlation to the opening width of the hand.
- The thumb dummy is always pulled back to its starting position by the retraction spring (black), if the control force is released before the thumb dummy moves further than the pathway apex.
- If the control force promotes the thumb dummy to pass the pathway apex and hence, leads to overflexion of the hand, the thumb dummy is shifted to the other pathway branch (lateral

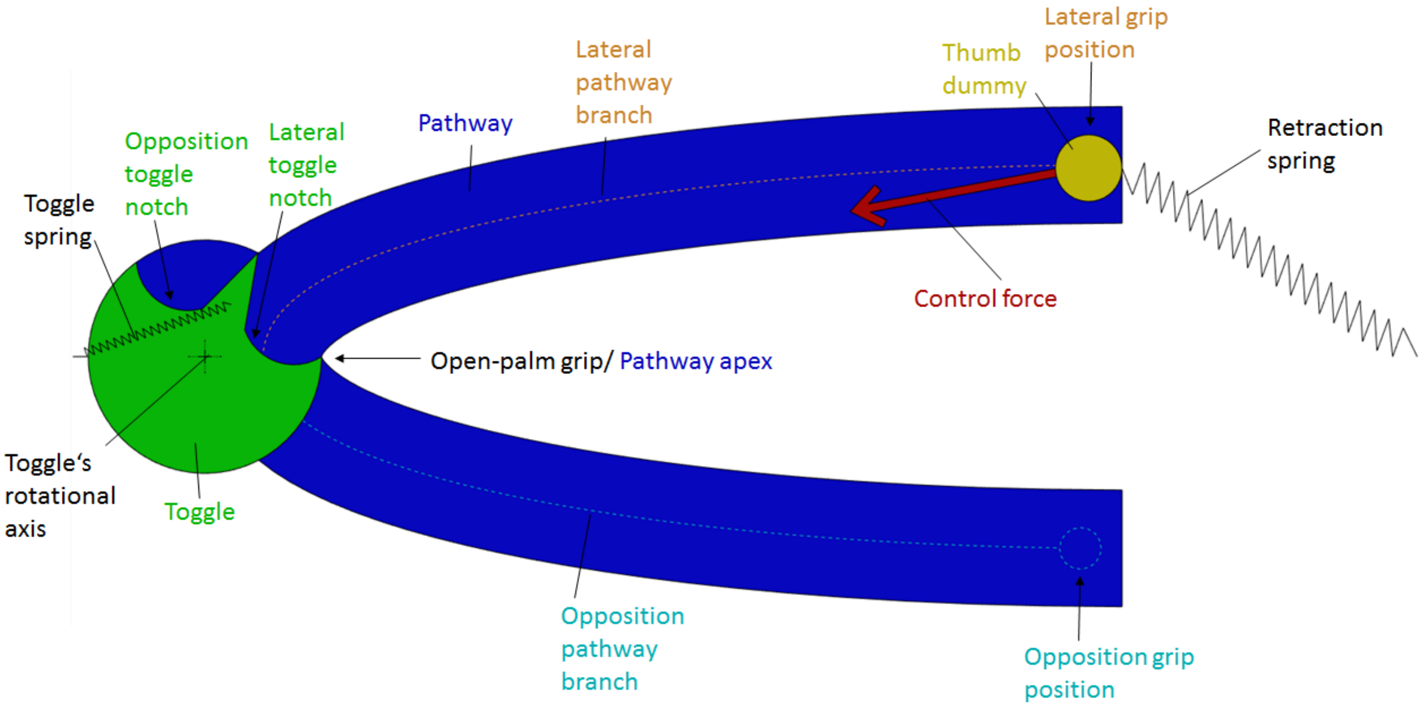


Fig. 2: Developed conceptual solution, which enables to switch between a lateral and an opposition grip of a VO body-powered prosthesis. The concept is based on the thumb dummy (yellow) being moved by the amputee's control force (red) within a parabolic pathway (blue). The two branches of the pathway each represent either the lateral (orange branch) or the opposition grip (light blue branch). The intersection of the two branches equals the open-palm grip, in which the hand is maximally opened. If the control force is stopped before the thumb dummy reaches the pathway apex, the retraction spring pulls the thumb back to its initial grip position (here: lateral grip). In case the control force moves the thumb dummy passed the pathway apex, the retraction spring drags the thumb dummy into the other pathway branch, by which the grip type is switched (here: from lateral to opposition grip).

pathway branch → opposition pathway branch) by means of the toggle (green).

- As soon as the thumb dummy reaches the pathway apex, it is located within the lateral toggle notch.
- When in this configuration additional force is applied to the thumb dummy, the thumb dummy pushes against the side wall of the lateral toggle notch and causes clockwise rotation of the toggle around the toggle's rotational axis.
- When the thumb dummy has passed the pathway apex, the orientation of the retraction spring changes.
- Once the lateral toggle notch, in which the thumb dummy is located in, matches the opposition pathway branch (light blue), the thumb dummy is pulled, in case of force relief, by the retraction spring along the opposition pathway branch into the opposition grip position (light blue circle). Consequently, the hand now conducts an opposition grip.
- The toggle spring (black) ensures, that the toggle is rotated into its second end position, in which the opposition toggle notch coincides with the opposition pathway branch, in order to have the mechanism prepared for a following change of grip type.

The switching procedure from the opposition grip to the lateral one is identical. In the following, the pathway branch, in which the thumb guiding pin is currently located in, will be named the "active pathway branch" and the other one respectively the "inactive pathway branch".

2.4 Elaboration

Figure 3 illustrates, how the components of the conceptual solution presented in Section 2.3 were realized in a 3D model constructed with the computer-aided design (CAD) software *PTC Creo Parametric 2.0*.

The way each component was exactly implemented in the 3D model will be described in the following:

- **Pathway**: The final parabolic pathway was curved in three dimensions. It was milled into a solid component, so that a pin can be guided within the two pathway branches. Each branch represents a different grip type: the upper branch equals the lateral grip and the lower one the opposition grip. At the end position of each branch, the hand is fully closed in the respective grip type. The intersection of both branches corresponds to the open-palm grip, which equals

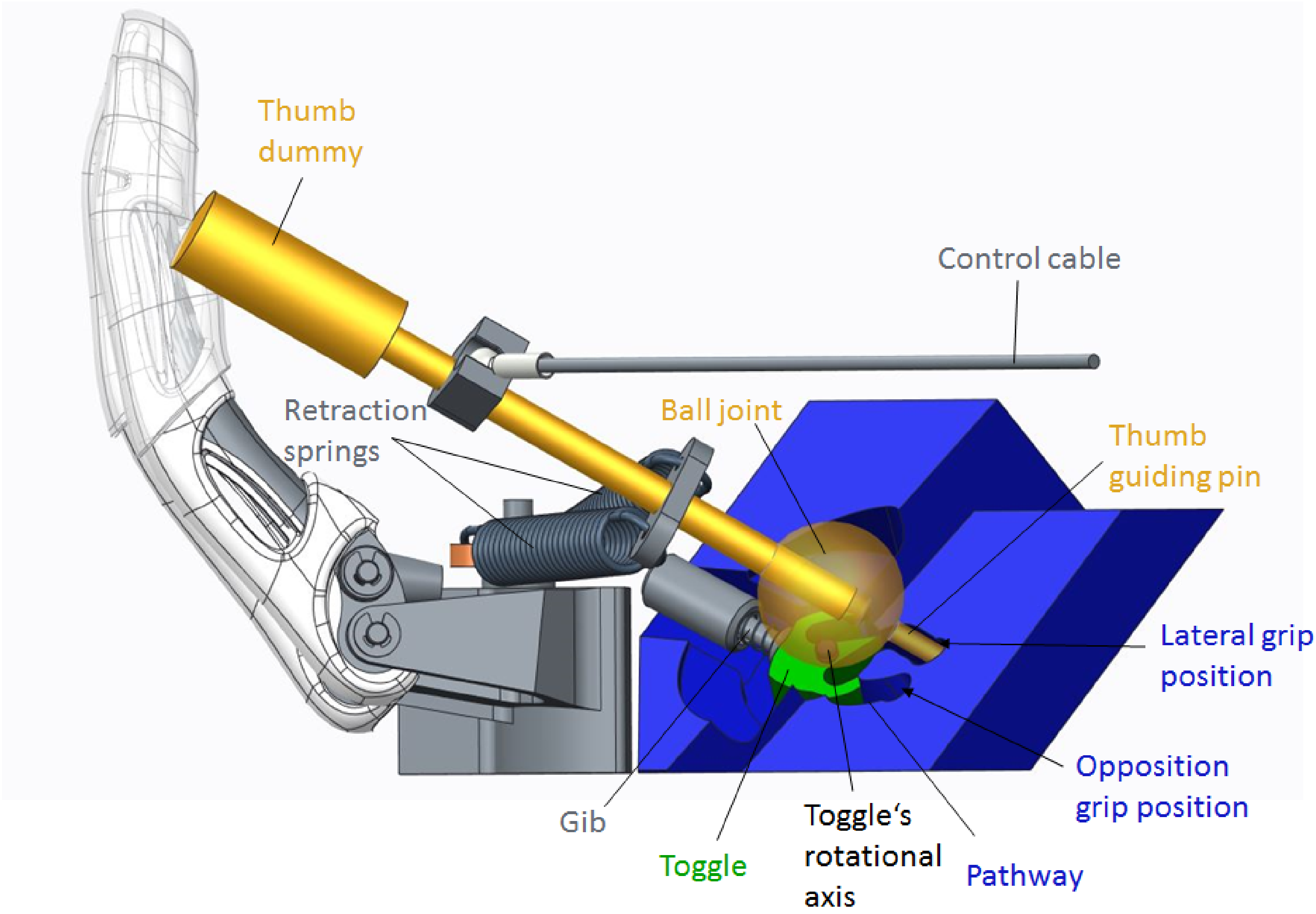


Fig. 3: Realization of the conceptual solution in a 3D model as part of a left hand prosthesis, which conducts a lateral grip. The thumb (yellow) is equipped with a stationary ball joint. Its movement is determined by the movement of the thumb guiding pin, which extends the thumb dummy below the ball joint. The thumb guiding pin moves within the milled pathway (blue), of which each branch defines a different grip type. The toggle (green) assists the thumb guiding pin to switch between the two branches, by which the grip type is varied.

the maximally opened hand. Here, a cylinder was milled into the solid component to provide a circular, planar locating surface for a toggle, which is responsible for transferring the thumb between the two pathway branches. A bore was drilled into the center of this planar surface to hold the axis of the toggle.
The other visible cuttings in the solid component are required for additional connecting elements.

- **Thumb**: The originally sliding thumb was equipped with a ball joint. The joint is fixed in place, so that any translational movement of the thumb is prevented. Consequently, changes in the grip type are accomplished by means of rotation of the ball joint leading to a tilting movement of the thumb dummy. The actual thumb movement is defined by the thumb guiding pin, which extends the thumb shaft below the ball joint. The thumb guiding pin can only move within the milled pathway described before. Due to the stationary ball joint and the thumb guiding pin being directed within the pathway, a distinct thumb movement can be accomplished with an increased position stability. Moreover, in addition to the change of thumb position, flexion of the thumb is also realized by the ball joint.
- **Toggle with spring**: The toggle comprises two notches at its front, a parabolic shaped tail at its back, a drilled hole to receive a rotational axis and a guiding pin on its bottom to define the toggle's range of motion.
The toggle is positioned on the planar circular surface within the circular cutting of the solid pathway component. The rotational axis of the toggle was pressed into the bore located on the center of this circular cutting. Consequently, the toggle can rotate around this axis and direct the thumb guiding pin from one pathway branch to the other one.
To receive the thumb guiding pin, the toggle comprises the two notches, of which each one extends the curvature of one pathway branch. After a change of the grip type the active pathway and the corresponding notch must match to enable a consecutive switching procedure. The two positions, in which one of the notches at a

time matches its corresponding pathway branch, define the toggle's range of motion and thus embody its two end positions.

The interaction of a round head gib and a compression spring is responsible for continuing to move the toggle to an end position once the thumb guiding pin has left the toggle notch. The compression spring is positioned behind the back of the toggle and carries the shaft of the round head gib interiorly. The head of the gib contacts the parabolic shaped toggle tail, so that it gets affected by the tail's curvature. When the toggle is rotated by means of the thumb guiding pin pressing against a notch wall, the curvature of the tail initially pushes the gib backwards. By doing so, the adjacent spring gets compressed. As soon as the head of the gib passes over the maximum protrusion of the toggle's tail, the compression spring can expand and hence, it supports the rotational movement of the toggle towards its other end position. Ergo, the toggle is continued to be turned even after the thumb guiding pin has moved from the toggle's notch into the second pathway branch.

A guiding pin, fixed to the bottom of the toggle, moves within a slot drilled in the solid pathway component, when the toggle is rotated. Owing to the boundaries of the slot, the movement of the guiding pin is restricted, thus defining the end positions of the toggle.

- **Retraction spring**: In order to achieve a high spring rate and hence, high gripping forces without requiring large diameter springs, two springs are utilized for retraction. Due to the design of their mounting, a spring could be positioned on each side of the thumb axis. In addition to high force values, the symmetrical implementation of the force application points was believed to be favorable for the system to reduce the drift of the thumb.

  A mounting plate for the retraction springs is screwed onto the thumb shaft above the ball joint. Hence, the second mounting is positioned on the palm dummy. Consequently, the springs always exert a pulling force on the thumb causing the hand to close as soon as the amputee releases the control force.
- **Force application**: Just as common body-powered prostheses, the control force is applied to the device by means of a Perlon cable. When the amputee tensions this cable, the hand gets opened. As soon as the maximum hand opening width is reached, additional control force applied by the user leads to a change of the grip type.

  The Perlon cable is fixed to the thumb shaft above the ball joint and is orientated in opposite direction to the retraction springs. The distance between the cable fixation and the ball joint's center of rotation influences the force required by the amputee to move the thumb: the higher the cable is positioned on the thumb shaft, the less force is needed.

  So far, the control cable is solely attached to the thumb shaft. Nevertheless, it is intended to combine the thumb control with the mechanic of the other fingers, so that in the long term only one control cable is needed to open the whole hand as well as to change the grip type.

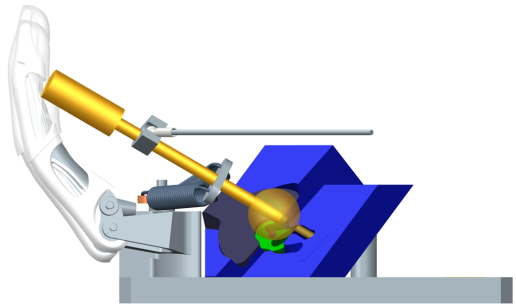
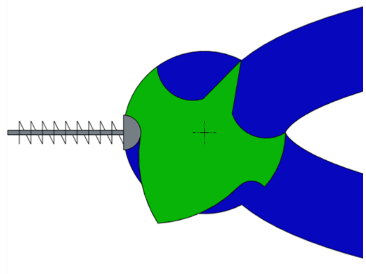
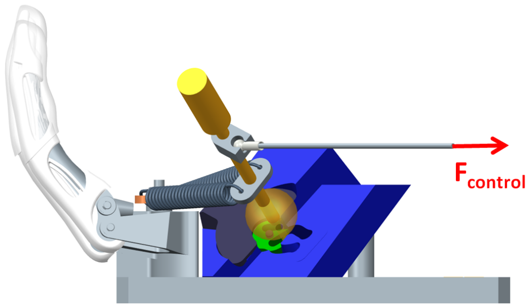
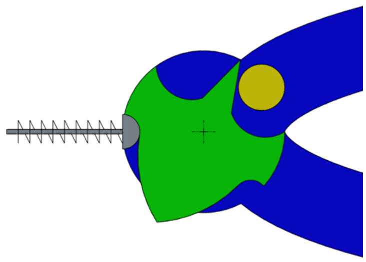
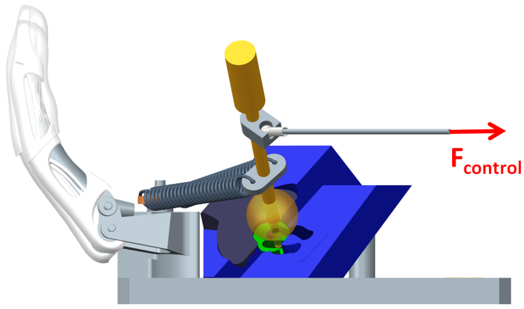
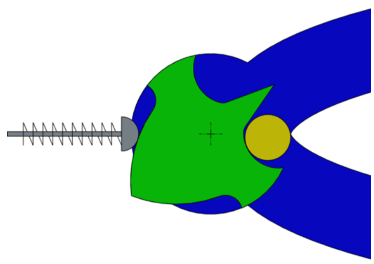
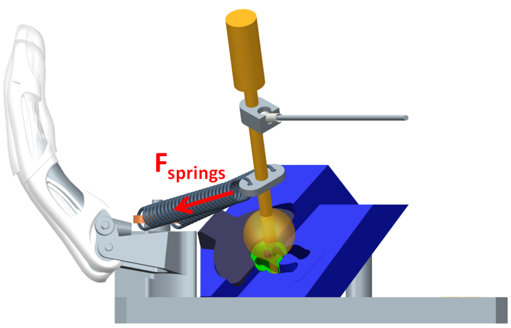
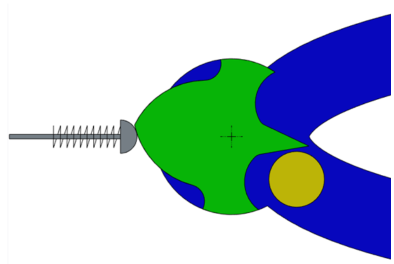
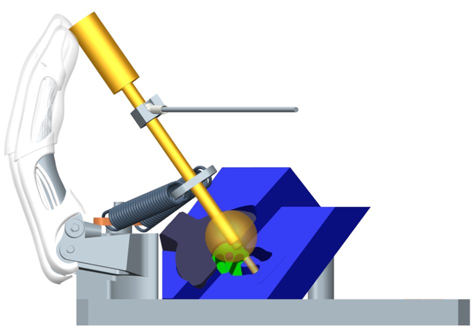
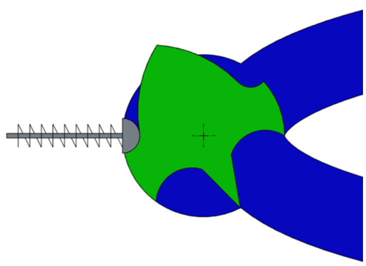
Additional components such as a stationary bearing for the ball joint or a lid to put over the toggle's tail to prevent tilting movements were added to the just described components in order to obtain a functional and manufacturable 3D model of the concept. As required, the components were linked by screw connections. Moreover, the mechanism was fixed to a base plate for rigid support. For an improved demonstration of the functionality of the system the final 3D CAD model was equipped with an index and a middle finger.

2.5 Mode of Operation

To elucidate the concrete mode of operation of the mechanism, consequent steps of a switching procedure from the lateral to the opposition grip are illustrated in Table 1 and described in the following. In Table 1 components not directly contributing to the switching (e.g. ball joint bearing) are faded in the final 3D model. For a better understanding, the interaction of toggle and toggle spring is added to Table 1 in the form of a 2D concept.

- **Lateral grip**: To realize the lateral grip, the thumb guiding pin is positioned in its lateral end position of the upper pathway branch. The toggle is rotated to its lateral end position, so that the lateral toggle notch matches the active, lateral pathway branch.
- **Thumb guiding pin entering toggle**: When the amputee tensions the control cable ($F_{control}$), the thumb guiding pin is guided along the lateral pathway branch towards the pathway apex. The thumb tip on the contrary is abducted moving towards its open-palm position. The retraction springs attached to the thumb shaft above the ball joint are tensioned due to this abduction movement. During the thumb's motion towards the open-palm position the thumb guiding pin finally hits the inclined wall of lateral toggle notch and gets directed to the notch's low point.
- **Clockwise rotation of toggle**: Additional force applied to the control cable causes the guiding pin to press against the wall of the notch's low point and hence, initiates clockwise rotation of the toggle. When the longitudinal axis of the thumb guiding pin aligns the pathway apex, the

TABLE 1: Consequent steps (left column) of a switching procedure from the lateral to the opposition grip are shown by means of the final 3D model (middle column) and the corresponding interaction between toggle and toggle spring by means of a conceptual drawing in 2D (right column). In the 3D model $F_{control}$ represents the force applied by the amputee to the control cable. $F_{springs}$ illustrates the total force exerted by the springs. The ball joint bearing and other connecting elements are faded in the 3D model for illustration purposes.

Description	Model	Conceptual Toggle
Lateral grip		
Thumb guiding pin entering toggle		
Clockwise rotation of toggle		
Thumb guiding pin exiting toggle		
Opposition grip		

maximum opening width of the hand is reached. When it is moved past the pathway apex and thus hyperflexes the thumb, a change of the grip type is initiated.

- **Thumb guiding pin exiting toggle**: When the lateral toggle notch, in which the thumb guiding pin is currently located in, matches the opposition pathway branch, the thumb guiding pin enters this branch in case the control force is released. Then the preloaded retraction springs $F_{springs}$ pull the thumb shaft towards the other fingers. Consequently, the thumb guiding pin gets dragged along the opposition pathway branch towards its opposition grip position.
- **Opposition grip**: After the thumb guiding pin exited the lateral toggle notch and in case the tip of the toggle has passed the pathway apex, the toggle spring continues the clockwise rotation of the toggle to the toggle's opposition end position. This way, the mechanism gets prepared for the next switch of the grip type.

Before the manufactured model is presented, the dimensioning of major components is depicted.

2.6 Dimensioning

The aim of this work was to develop a mechanism to vary the grip pattern as a first design step for a body-powered alternative to the Michelangelo Hand. Since the actual properties of the Michelangelo Hand are supposed to be realized in the long term, the thumb positions achieved with the designed mechanism should match the positions of the Michelangelo thumb for the corresponding grip. Therefore, the dimensioning of the switching mechanism was based on the CAD-files of the Michelangelo Hand. From these, the coordinates of the thumb finger tip and the orientations of the thumb's longitudinal axes in the lateral, in the open-palm and in the opposition grip were extracted. The Michelangelo thumb comprises two longitudinal angled axes, as its interphalangeal joint (IP) is designed with a constant preflexion.

In addition to the extracted coordinates and axes, the hand chassis was transferred as palm dummy to the new design to retain the correct relative positions between the thumb finger tip and the hand palm. Though the hand chassis was adapted and simplified for the switching mechanism. Based on the extracted coordinates of the thumb finger tip in the different grip types and the corresponding position of the hand chassis, the switching mechanism was constructed. Especially the position of the ball joint's center of rotation as well as the exact geometry of the pathway are highly influenced by the extracted properties as described in the following.

2.6.1 Position of the Ball Joint

Physiologically, the rotational movement of the human thumb from the lateral, the open-palm or the opposition position to another one of these extreme positions is named circumduction. In literature the thumb's circumductional movement is approximated as a cone with the cone apex positioned in the carpometacarpal joint (CMC). Though, the thumb's kinematic is physiologically an interaction of the thumb's CMC and its metacarpophalangeal thumb joint (MCP) [14]. For simplicity, the two physiologically interacting thumb joints were realized in the designed mechanism as one ball joint. Its position was determined by means of the cone approximation of the thumb's circumductional movement as illustrated in Figure 4. Here the longitudinal axes of the index and the middle finger were added for a better perception of the hand orientation.

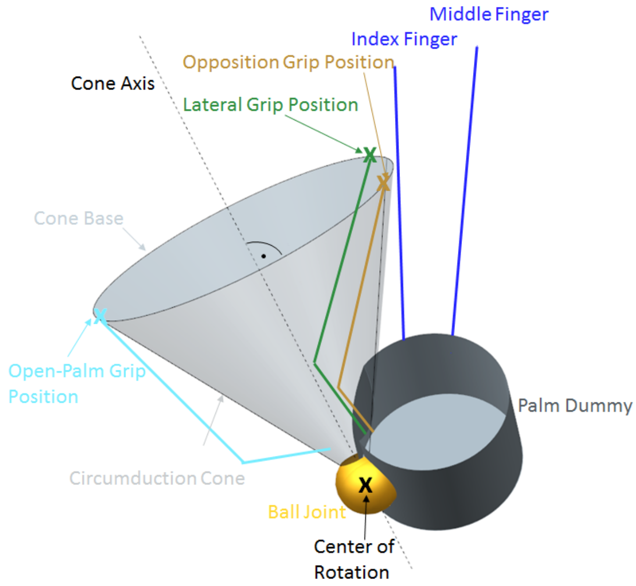


Fig. 4: Deviation of the position of the ball joint based on the approximation of the thumb's circumduction movement between the lateral, the open-palm and the opposition grip as a cone with the apex in the CMC [14]. The points (green = lateral grip position, turquoise = open-palm grip position & orche = opposition grip position) representing the thumb finger tip during the different grip types span the base of the cone. The ball joint (yellow) is positioned on the cone axis (dashed black line) which was constructed orthogonal to the cone base.

As shown in Figure 4 the points representing the thumb finger tip in lateral position (green), in open-palm position (turquoise) and in opposition position (orche) span the cone base. The cone axis (dashed black line) was constructed orthogonal to the cone base through its center point. The apex of the cone and hence, the ball joint's center of rotation could be positioned anywhere along this axis. Depending on its position, the length of the thumb's shaft was adjusted, so that the coordinates of the tip of the Michelangelo thumb were always reached. A height of about 86 mm was chosen for the cone, so that the

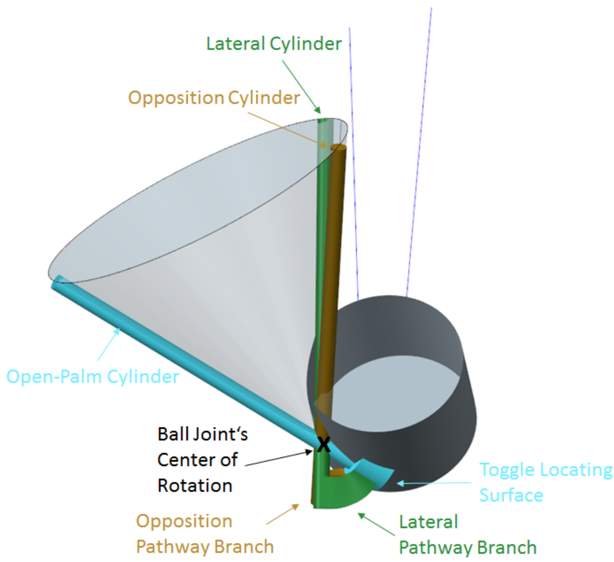


Fig. 5: Deviation of the exact pathway geometry based on the chosen position of the ball joint. For this three cylinders were implemented in the design aligning along the axes, which each connect a point of the thumb finger tip with the ball joint's center of rotation. The volumes of the cylinders were extended passed the ball joint and hence, define the end positions of the thumb's guiding pin. By connecting the lateral cylinder (green) as well as the opposition cylinder (orche) to the open-palm cylinder (turquoise) a negative image of the pathway was derived.

ball joint is positioned approximately in the middle of the palm dummy volume leaving space for the retraction springs above and space for the pathway below the ball joint.

2.6.2 Pathway Geometry

Based on the chosen ball joint position the exact pathway geometry was generated (Figure 5). For this, axes were created, which each connect one point of the thumb finger tip in a particular grip with the ball joint's center of rotation. Identical cylinders were aligned along these axes. The volumes of the cylinders were extended passed the ball joint's center of rotation since the pathway was intended to be located below the joint. By means of the lateral cylinder's (green) and the opposition cylinder's (ocher) parts below the ball joint, the two grip positions of the thumb guiding pin were created. The lateral cylinder as well as the opposition cylinder were connected to the open-palm cylinder creating a negative image of the pathway, which geometry was milled in the solid pathway component. Consequently, the pathway was designed such, that the thumb always moves from its current active grip type towards the open-palm grip. This maximally opened hand position also defines the point of grip type switch. For this reason, the open-palm cylinder was eccentrically enlarged to construct a locating surface for the toggle. By means of the offset of the enlargement from the center axis of the open-palm cylinder, it is determined how the pathway branches merge into the toggle's locating surface. This, in turn, had to be well adjusted to the toggle design in order to ensure a continuous functionality of the system.

When the tip of the toggle aligns with the pathway apex, the toggle is in its dead-center position. In this position, singularity occurs, because the rotational direction of the toggle is not unique. Since no movement can proceed from the retraction springs in this position, the occurrence of the toggle rotation stops in this configuration should be prevented in the designed mechanism. If the thumb guiding pin stops pushing against the notch wall before the toggle's tip reaches the pathway's apex, the toggle will always be rotated into its initial end position by the toggle spring. In case the toggle's tip has passed the dead-center position before the thumb guiding pin stops pushing, the toggle spring will turn the toggle to its second end position. Latter is required for the continuous functionality of the system. Consequently, the geometry of the pathway as well as the toggle were designed such, that the toggle's tip passes the dead-center position before the thumb guiding pin moves into the other pathway branch.

The remaining components of the designed mechanism were adapted to the ball joint and the geometry of the pathway with a view to occupy as little installation space as possible.

The dimensions of the springs required as retraction springs as well as the one needed as toggle spring were calculated roughly. Because of most of the springs' properties being adaptable, the final 3D CAD model, which was manufactured, had been designed very variable as well. Thus, multiple springs could be tested with regard to e.g. different positions, orientations or pretensions. Finally, the most suitable spring configuration was selected.

Based on the 3D CAD files of the mechanism the *Prototype Development Center* of Otto Bock manufactured a model, which was tested regarding its functionality and its resultant properties were estimated.

3 Results

In the following the resultant manufactured model and its adaptable characteristics are presented. Furthermore, the properties estimated to result from the selected configurations are presented. Lastly, the developed device is compared to the Michelangelo Hand.

3.1 Manufactured Model

A functional model of the designed mechanism has been manufactured as part of a replacement of a left

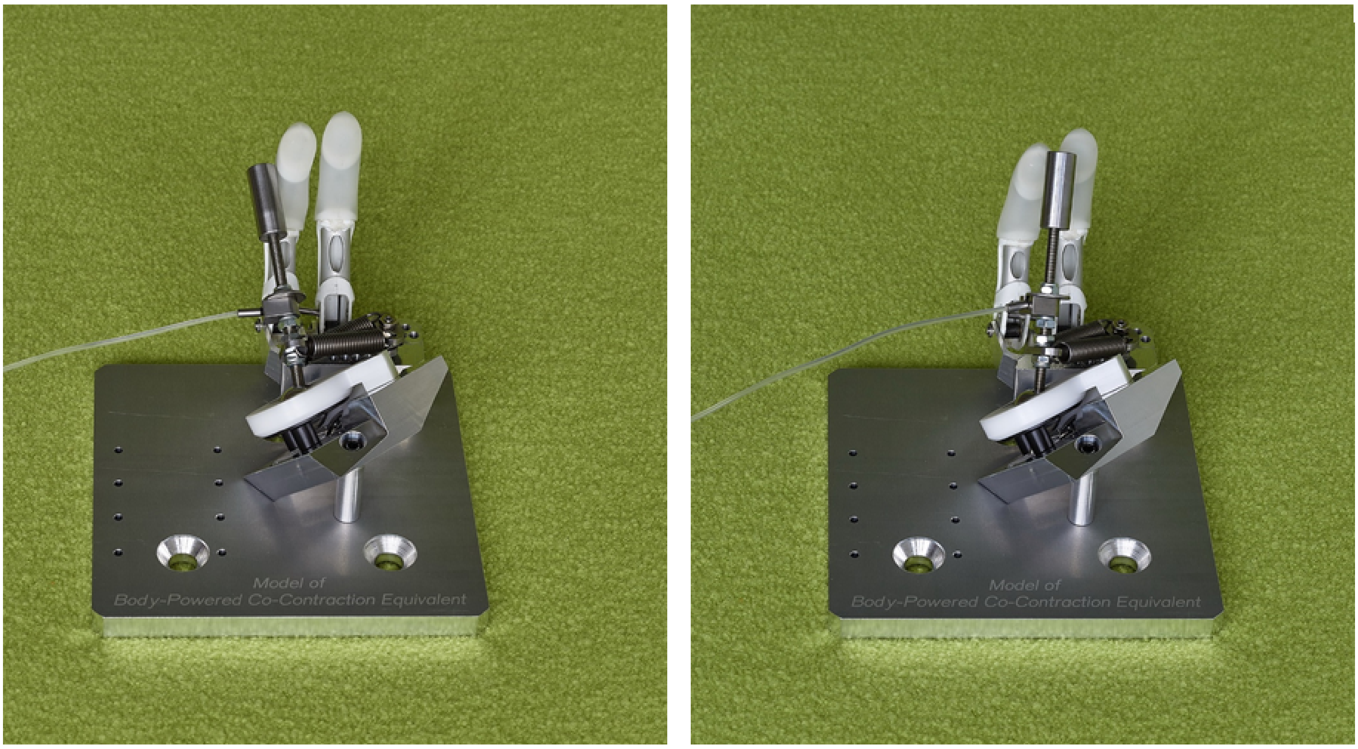


Fig. 6: Manufactured model conducting a lateral grip (left) and an opposition grip (right)

hand. In Figure 6 it can be seen in its lateral as well as in its opposition grip. The index and the middle finger of the Michelangelo Hand were mounted to the manufactured model of the designed mechanism for illustration purposes. Even though it is intended to combine the mechanic of all other fingers with the thumb control in the long term, in this manufactured model the attached fingers can solely be moved passively.

The mechanism is applicable for a VO device. When the attached Perlon cable was operated both the opening of the hand as well as the switching between the lateral and the opposition grip were performed. Consecutive switches of the grip types were conducted, wherefore the functionality of the mechanism could generally be demonstrated in practice. However, with the manufactured model it has occurred a few times, that the toggle was moved back to its initial end position after the thumb had switched the pathway branch. Consequently, it was not possible to change the grip time an other time, because the guiding pin hit against a toggle wall instead of being able to enter a toggle notch. In this case the toggle had to be manually moved to the correct end position.

3.2 Properties of the Manufactured Model

The model was produced in a very adjustable way, in order to be able to test different spring configurations. For example the mounting plate of the retraction springs was screwed to the thumb's shaft, so that the lever arm and the angle of the spring forces could be varied. Several bores were drilled in the palm dummy in order to be able to also change the position of the other attachment of the retraction springs. This was conducted both to be able to try different springs and to vary their pretension. Likewise, the toggle compression spring had been incorporated in a setscrew. Hence, the preloading of the toggle spring can be changed by varying the setscrew penetration depth. In addition to the springs' characteristics, the point of application of the control force was also realized variably in the model, as the mounting plate of the cable can be moved along the thumb shaft [2].

Finally, the tension spring *Z-111I* (1.25 X 9.2 X 43.3; EN 10270-1; R= 2.02 N/mm), manufactured by *Gutekunst + Co.KG*, was utilized as the two retraction springs. One mounting of the retraction springs was fixed on the thumb shaft at a distance of around 25 mm to the ball joint's center of rotation. The other attachment of the retraction springs were positioned on the palm dummy in such a way, that the installtion length l_1 of the springs measures 46.6 mm in the lateral and 48.6 mm in the opposition grip. *Gutekunst + Co.KG*'s compression spring *D-049* (0.4 X 4.4 X 11.2; EM 10270-1; R = 0.471 N/mm) was implemented with a preload force of 0.989 N in the model to operate as the toggle spring. The control cable was

2. The large diameter bores in the base plate, which can be seen in Figure 6, serve as attachment points for suctions knobs, by which the base plate can be fixed to the table. The remaining spare bores are backups to enable to test compression springs as retraction springs.

TABLE 2: Estimated hand properties and measured mass

Properties		Value	
		Lateral grip	Opposition grip
Opening Width [mm]		117.5	
Max. Cable Force [N]		120.2	
Max. Cable Excursion [mm]		43.7	41.9
Max. Grip Force [N]		23	
Pinch Force [N] at	10 mm	8.3	10.5
	20 mm	10.7	13.0
	30 mm	13.2	15.5
Mass [g]		372	

mounted to the thumb shaft in a distance of around 42.9 mm from the ball joint's center of rotation.
With these arrangements, properties as the maximum opening width, the maximum cable force, the maximum cable excursion or the pinch forces at an opening width of 10 mm, 20 mm or 30 mm were mathematically estimated for both grip types. In addition to these estimations, the mass of the model was measured. All derived properties are summarized in Table 2.

In the open-palm position, which characterizes the maximum opening width of the hand, the tip of the thumb and the one of the index finger span a distance of approximately 117.5 mm. To reach the maximally opened hand configuration, the thumb finger tip has to be moved by 102.3 mm from the lateral grip position and by 97.8 mm from the opposition grip position.
To operate the system a maximum force of 120.2 N has to be applied to the control cable. Additionally, the control cable is displaced by 43.7 mm when starting from the lateral grip and by 41.9 mm when starting from the opposition grip.
Generally higher pinch force values were estimated for the opposition grip compared to the the lateral grip. With the thumb finger tip being moved about 10 mm from a closed hand position, a pinch force of 8.3 N was calculated for the lateral and of 10.5 N for the opposition grip. A pinch force of 10.7 N could be predicted for the lateral grip and of 13.0 N for the opposition grip, when the thumb finger tip is moved about 20 mm. Pinch forces of 13.2 N for the lateral grip and of 15.5 N for the opposition grip were estimated in case of the thumb finger tip being moved about 30 mm.
All model components apart from the base plate measure together a total mass of 372 g.

So far, it has been illustrated, that the grip type of the developed mechanism can be varied between a lateral and an opposition grip (Figure 6). Furthermore, some properties of the two hand grips have been estimated (Table 2). In the following, it is investigated, how well the developed device approximates the functionality of the Michelangelo Hand, to which the designed mechanism is considered to offer a

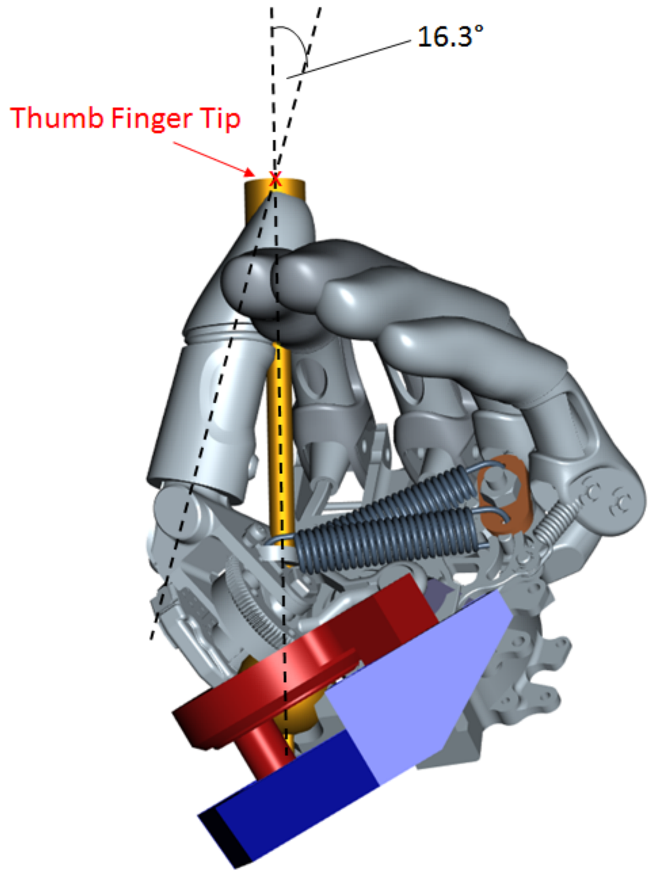


Fig. 7: Comparison of the developed device and the Michelangelo Hand in lateral grip by means of CAD-files regarding the alignment of the thumb finger tips, the longitudinal axes of the thumbs and the size of the complete devices

body-powered alternative in the long term.

3.3 Comparison to the Michelangelo Hand

By means of the CAD-files the designed devices can be compared to the Michelangelo Hand regarding its size and its thumb positions. Both hands are presented in Figure 7 exemplarily in the lateral grip.

The two hands shown in Figure 7 seem to be superposable. A similar view is received with both devices conducting an opposition grip. Both times the thumbs penetrate each other at their distal part to finally, have their designated finger tips coincide. Yet, the distal longitudinal axis of the Michelangelo thumb and the longitudinal axis of the thumb of the new designed device measure a deviation of 16.3° in both grip types. Apart from this, solely a part of the solid component, in which the pin pathway is milled, and the ball joint bearing protrude from the chassis of the Michelangelo Hand. The ball joint and the retraction springs can give the impression of being part of the Michelangelo Hand. The toggle and its resetting system even fully disappear in the Michelangelo Hand.

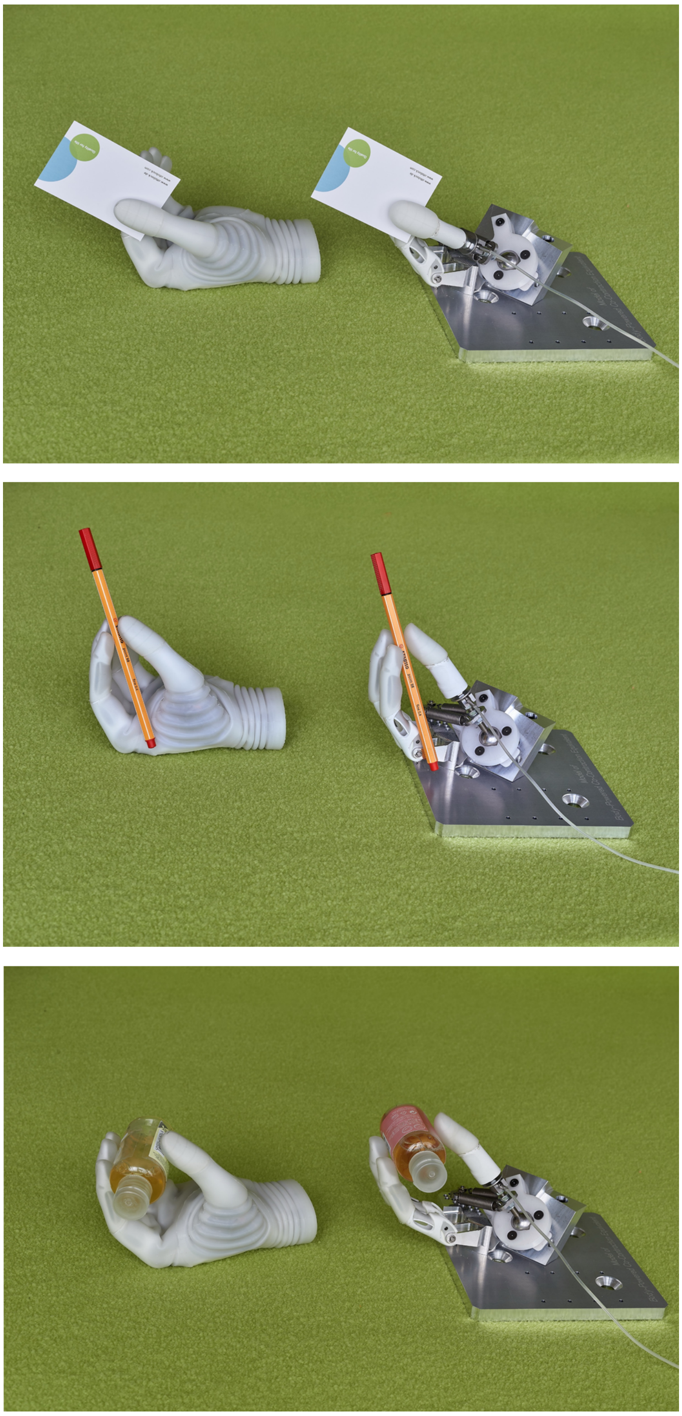


Fig. 8: Comparison of the developed device and the Michelangelo Hand by means of manufactured models in practice regarding the lateral pinch grip (top), the opposition pinch grip (middle) & the opposition power grip (bottom)

How similar both devices perform in practice is displayed in Figure 8. Here both hands laterally pinch a business card (top), hold a pen with an opposition pinch grip (middle) or a small bottle with an opposition power grip (bottom) [3]. The resultant grip patterns appear very similar with respect to the thumb approaching the other fingers. Though small deviations regarding the rotational orientation around the thumbs longitudinal axis can be seen in the opposition grips (Figure 8, middle and bottom).

4 Discussion

4.1 Manufactured Model

Generally, a functional mechanism was presented, in which solely one control cable is utilized to open the hand as well as to switch between a lateral and an opposition grip type. With a few exceptions, multiple cycles of switching the grip type could be conducted consecutively. However, a few times the switching procedure was inhibited, because of the thumb guiding pin hitting against an exterior wall of the toggle rather entering one of the toggle's notches. In these cases, the toggle was located in its wrong end position, so that one of its notches matched the inactive pathway branch rather than the active one. The occurrence of this implies, that the toggle's tip had not passed the system's dead-center position before the thumb guiding pin exited the toggle's notch even though this characteristic has been taken into account when dimensioning the geometry of the pathway and the toggle. This time, though, the malfunctioning of the mechanism is caused by a reduction in the diameter of the guiding pin, which had in the end been conducted to prevent the pin from jamming inside the notch. As a result, the thumb guiding pin was in fact too small sized compared to the design of the toggle and its notches. Therefore, it was possible for the guiding pin to slip out of the notch way before it was intended to. This reduction of the guiding pin's diameter has to be eliminated in future prototypes.

In consequence of the size deviation between thumb guiding pin and toggle notches, it is recommended for the existing model to continue the force application until no further thumb movement can be observed. This way, the toggle is pushed actively to its other end position. Hence it is ensured, that the toggle's tip has passed the dead-center position before the thumb guiding pin can switch into the other pathway branch. When the controlling force is then released, the thumb guiding pin, driven by the retraction springs, pushes against the medial notch wall causing it to rotate backwards. As soon as the

3. A lateral power grip could not be captured since in this grip type also the ring and the small finger would have been required to hold the object in position.

active notch and the nearer pathway branch create a common space sufficient enough for the thumb guiding pin to slide through, it exits the notch into the currently reached pathway branch. Subsequently, the compression spring acts on the toggle and turns it this time into the correct end position.
Keeping this recommendation in mind, the manufactured model can be regarded as a successful demonstration of the functionality of the designed mechanism.

Estimations of potential hand properties revealed for the two grip types, differences in the maximum cable excursion and the obtained pinch forces. Less cable excursion is required for the opposition grip, whereas higher pinch forces are achieved. The cable excursion is predefined by means of the Michelangelo Hand's thumb positions and therefore, cannot be adapted for the mechanism. The differences in the obtainable pinch forces reveal, that the retraction springs have a higher pretension in the opposition grip than in the lateral one. This could be adapted by shifting the spring mounting attached to the palm dummy in radial direction. Because a higher grip strength is more often required in an opposition grip rather than a lateral grip, the current configuration of achieving higher forces in the opposition grip could present a nice feature for a final design.

4.2 Comparison to the Michelangelo Hand

When comparing the developed mechanism to the Michelangelo Hand in practice, the way the thumbs approach the other fingers when conducting a lateral or an opposition grip appear very similar. Solely, a small deviation in the thumb's orientation around its longitudinal axis was noticeable. Considering the CAD files, the finger tips of the thumbs coincide perfectly in both grip types. Nevertheless, an angular deviation of 16.3° was determined between the longitudinal axis of the designed mechanism and the distal longitudinal axis of the Michelangelo thumb in lateral as well as in opposition grip. This large angular deviation is mainly attributed to the Michelangelo thumb being constructed with a constant flexion in its IP, which was not yet implemented in the developed mechanism. When in the lateral grip the alignment of the thumb was adjusted to the corresponding one of the Michelangelo thumb by implementing a constant flexion in its IP, the axes of both thumbs matched perfectly. The validation of the axes' alignment in the opposition grip yet still revealed a deviation angle of 4.8°. This deviation, in turn, can be attributed to the thumb's drift. As long as the drift of the thumb still leads to a natural appearance, a deviation between the thumb axis of the new developed mechanism with respect to the one of the Michelangelo thumb less than the limit of 5° is acceptable.

4.3 Verification of the Design Requirements

In the following it is examined, whether and to what extend the designed mechanism fulfills the design requirements. The design requirements referring to the costs and the robustness of the device are not applicable at the current state of development and therefore, will not be assessed.
In addition to the validation of the design requirements, it is evaluated how the developed mechanism is estimated to perform compared to other commercially available VO hands [4].

1) **Function**: A body-powered prosthetic VO hand was developed. Based on the overloading principle the grip type of the device can be switched between a lateral or an opposition grip. The achieved grip types approach the ones of the Michelangelo Hand. Nevertheless, the exact alignment of the thumb's longitudinal axis of the developed device and the distal longitudinal axis of the Michelangelo thumb reveal a deviation of 16.3°, which is more than three times the limit of 5° as defined in the design requirements. However, in Section 4.2 a solution is suggested how the maximum deviation angle can be reduced below the limit of 5°.
In contrast to the designed mechanism, commercially available VO hands are constructed immutably in an opposition grip. Consequently, the opening width of these hands is distinctly defined as the distance between the thumb and the opposing index finger or index and middle finger. The majority of the devices comprise an maximum opening width around 80 mm [8]. However, in this designed device the thumb moves from its currently activated grip towards the open-palm grip, in which the thumb is fully abducted in radial direction and lies in the palmar plane with the other fully extended fingers. Consequently, the designed device even simulates the physiologically, maximally opened hand position. Anyway, following the definition of the opening width of the other VO hands, a distance of about 117.5 mm could be measured in the open-palm grip. To achieve this maximally opened position, the thumb finger tip has to be moved about 102.3 mm from the lateral grip and 97.8 mm from the opposition grip. Based on this, an opening width of 80 mm can be guaranteed.
A grip force of at least 20 N was set to ensure great usability of the designed device in everyday life. This requirement is meet by the manufactured model since the maximum

4. It has to be kept in mind that the properties of the designed mechanism are solely estimated values. Its actual performance still has to be tested especially when the finger mechanics has been coupled to the control cable as well.

achievable pinch force was estimated to be 23 N. Because of the pinching force in VO hands being highly depended on the current opening width, commercially available VO hands are generally compared by measuring the pinch force at an opening width of 10 mm, 20 mm and 30 mm. The VO hands presented in Smit et al. [8] reveal on average a pinch force of 10.6 N (at 10 mm), of 10.2 N (at 20 mm) and of 9.8 N (at 30 mm). Apart from the lateral pinch force at an opening width of 10 mm, the pinch forces of the developed design were estimated to be higher than the average values of the VO hands presented in Smit et al. [8]. Even though the lateral pinch force at an opening width of 10 mm is with 8.3 N lower then the average pinch force of available VO hands, it is more than 2.5-times higher then the pinch force of the RSL Steeper VO Hand [8].

To sum up, the designed mechanism reveals functional properties, which are equal to or better than the ones of commercially available VO hands.

2) **Control**: In the designed mechanism the same control cable is operated to open the hand and to switch the grip type. Since the mechanic of the fingers is intended to be connected to the same cable, which is currently solely attached to the thumb, the final hand only requires one control cable. Consequently, Otto Bock's standard harness *21A36=1* can be used to operate the designed mechanism.

3) **User group**: Solely if the control cable requires a maximum force of less than 140 N and a maximum cable excursion of less than 53 mm, the device can be operated by below-elbow amputees [8], [9], [10]. For the designed mechanism a maximum cable force of 120.2 N was estimated. Furthermore, to change from the lateral grip to the opposition one, a cable excursion of maximal 43.7 mm is required. To conduct the switch of the grip type in reverse, the amputee solely needs to displace the cable by 41.9 mm. Based on these estimations, the mechanism can be applied by below-elbow amputees. Compared to commercially available VO hands the mechanism requires a control force similar to the ones of the *Hosmer Soft VO Hand* and the *RSL Steeper VO Hand*, which are considerably higher than the forces needed to operate the other devices described by Smit et al. [8]. Since the finger mechanic will still be added to the control cable of the designed mechanism, the maximum cable force will further increase. However, in the new design the maximum cable force refers to the force values required for the switching of the grip type during which the hand opening width has already exceeded the other ones. Thus, the maximum cable forces are not determined under the same conditions. Nevertheless, in the future it has to be evaluated, if the implemented features justify the increased required cable forces. The required cable excursion are close to the average cable excursions of the commercially available VO hands.

Since the mechanism solely comprises a single control cable, the mechanism can be operated by uni- as well as bilateral below-elbow amputees. In order to also enable above-elbow amputees to use the device, the maximum force, required for operating the cable, cannot exceed 138 N as derived from measurements conducted by C. L. Taylor [10] [5]. Since the current estimated force equals 120.2 N, the device generally bears the potential to be also used by above-elbow amputees.

4) **Comfort**: The weight of the prosthesis highly influences its comfort. Consequently, the device should be as light as possible. For the designed mechanism a mass of 372 g was measured, which is about 1.8-times higher than the mass defined in the requirements. The model is also heavier than all the other available VO hands. However, the goal of this study was to present a functional model rather than an actual prototype of the design. Therefore, the focus of this study was put on a working mechanism rather than a lightweight design. The model, though, still bears high potential to be optimized with respect to its mass. First of all, it comprises redundant material (e.g. the palm dummy being constructed as a solid component or the solid pathway component), which needs to be eliminated. Moreover, parts of the mechanism (e.g. the ball joint bearing) need to be resized, whereby the mass will slightly be reduced. Lastly, a lightweight design is an important criterion to be considered, when selecting the proper materials for the final components.

In case there is a deviation of more than 4 mm in the initial displacement of the control cable between both grip types, the user would have to readjust his/her harness in order to ensure the usability of the device. This would be very cumbersome for the amputee and hence, influences the comfort of the usage of the device. So far this characteristic has not yet been validated. However, no cable deviation is expected since the concept of the mechanism is based on a

5. The derivation of the maximum control force, an above-elbow amputee is capable of, is comparable to the derivation of the control cable force of a below-elbow amputee as described in Section 2.1. However, since above-elbow amputees most often apply shoulder shrug for prosthetic control, the deviation was based on the force value of 276 N, which can be reached by means of shoulder shrug [10].

constant pulling direction.
To further improve the comfort of the usage of the mechanism, obstacles could be incorporated in the design, which alert the user that the maximum hand opening width is achieved. Hence, the amputee is warned, that additional force applied to the mechanism will cause a switch of the grip type. This way, the user is not required to carefully monitor the opening of the hand and the mental load for the device usage is reduced.

5) **Appearance**: Figure 7 illustrates the mechanism approximating the size of the Michelangelo Hand. However, in order to actually acquire the size of the Michelangelo Hand, especially the solid pathway component and the ball joint bearing of the designed mechanism need to be scaled down. Nevertheless, it is believed, that the mechanism can be adapted in such a way, that it finally resembles the size of the Michelangelo Hand.
6) **Transferability**: Due to the mechanism being based on a distinct pathway, the concept cannot be easily applied to switch between other prosthetic hand movements as wrist rotation and prehension.

In summary it can be stated, that the designed mechanism fulfills all critical requirements, which is why the design goal has been achieved. Beyond this, it has been presented, that the development meets some of the "should"- and even "could"-requirements. Moreover, small adjustments have been suggested, by which the mechanism is expected to meet all design specifications apart from three "could"-requirements (the complete circumduction movement, the two-way control and the transferability).

5 Conclusion

In order to combine the body-powered advantages of lightweight, robustness, low costs and extended proprioceptive feedback with the myoelectric feature of multiple degrees of freedom and hence, to establish in the long term a body-powered alternative to Otto Bock's Michelangelo Hand, this study is focused on the design of a mechanism, which enables a body-powered user to select between a lateral and an opposition grip as easily as with the myoelectric co-contraction.

- **Concept**: A body-powered VO device was constructed, in which the overloading of its prehension control cable initiates a switch of the grip type. The mechanism is based on a thumb guiding pin, which moves within a parabolic-shaped pathway. Each pathway branch represents one of the grip types. Consequently, a change of the grip type results from the thumb guiding pin changing the pathway branch.

- **Manufactured model**: The aim of this project is reached since a model illustrating the general functionality of the developed mechanism has been manufactured. The model meets more than just the critical requirements and it has the potential to meet also almost all important as well as desired requirements. However, to achieve this, the model still requires adaptations and optimization regarding its size and weight.

- **Comparison to Michelangelo Hand**: The lateral as well as the opposition grip achieved with the designed device are very similar to the corresponding grip conducted with the Michelangelo Hand. By implementing a thumb, which comprises a preflexion in its IP, the alignments of the thumbs' longitudinal axes will further improve.

- **Comparison to commercially available VO hands**: Based on estimations of its properties the developed device is expected to perform equally well as commercially available VO hands. Though it facilitates a clearly improved functionality and appearance by providing two different grip types. However, the actual characteristics of the mechanism still have to be proven in practice with a complete hand as prototype.

6 Prospects

Apart from the already presented suggestions for improvements, two additional characteristics need to be elaborated and added to the device in order to achieve an acceptable prosthetic hand: first of all the routing of the thumb's control cable needs to be revised since the cable currently stretches from the dorsal side of the thumb, which is highly conspicuous. Secondly, the mechanic of the other fingers needs to be developed, so that they can be actively manipulated with the same control cable as the thumb.
In the following, for each characteristic a concept is presented, how it could potentially be realized in the body-powered alternative to Otto Bock's Michelangelo Hand. Both concepts are illustrated in Figure 9.

6.1 Potential Routing of the Thumb's Control Cable

There are two major characteristics, which have to be considered for the routing of the thumb's control cable: first of all, the cable needs to run from its fixation on the thumb in proximal direction. Only if it stretches along the longitudinal axis of the arm towards the shoulder, it can be applied to the standard

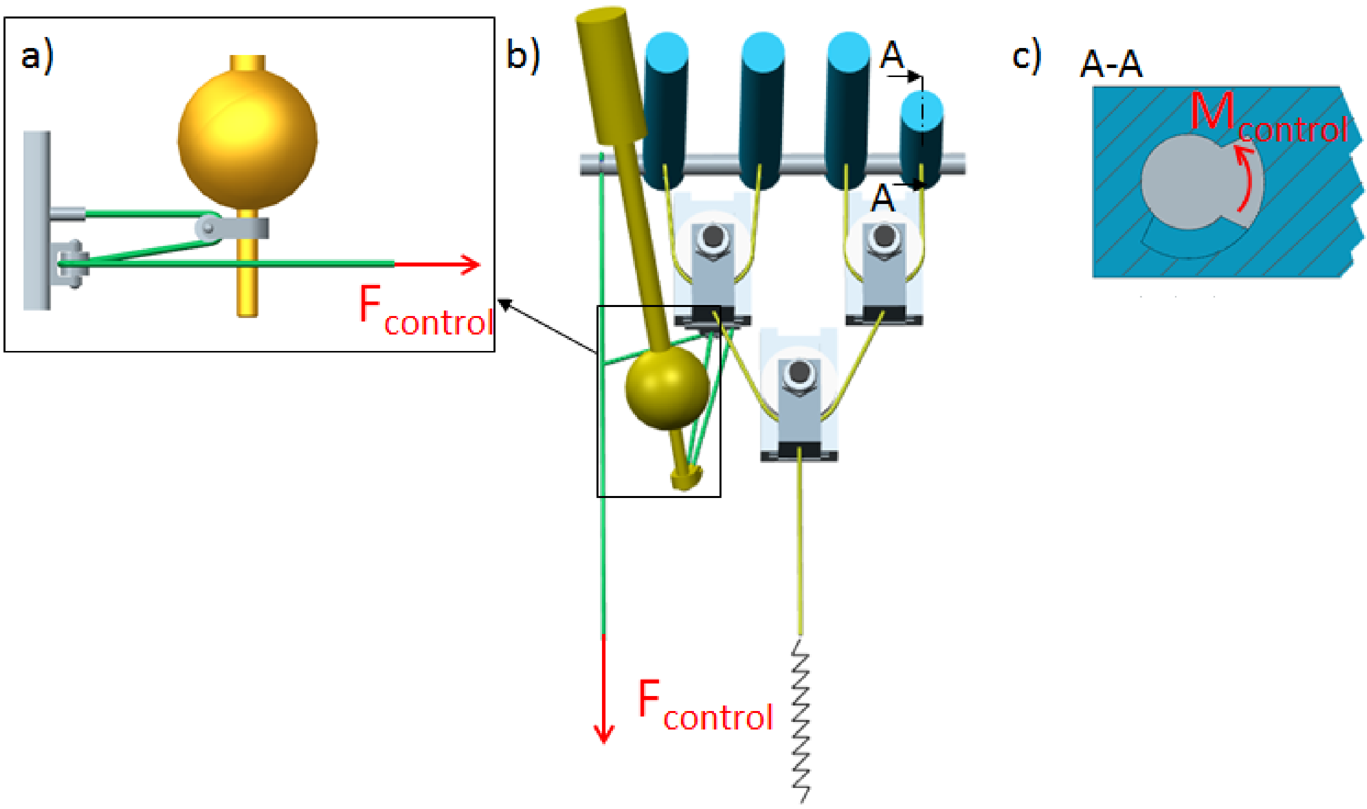


Fig. 9: Potential thumb cable guiding and finger mechanic for an acceptable VO hand, which comprises solely one main control cable for the operation of the device.
a) Thumb cable guiding: The thumb cable is located below the ball joint. It is attached to the palm dummy and stretches to a movable pulley fixed on the thumb guiding pin. A deflection pulley mounted to the palm dummy directs the cable in proximal direction.
b) Finger mechanic: The thumb control cable fuses with the finger control cable to one main control cable, so that the opening of the hand is controlled solely by one cable. When the main control cable is tensioned, it causes the shaft, on which the fingers are positioned on, to rotate counterclockwise. The fingers are pushed by entrainers to follow this rotation. The fingers of the hand are differential coupled by means of floating pulleys, by which the closing of the hand is conducted in an adaptable manner. When the fingers are pulled by the spring to rotate clockwise, they push against the entrainers and hence, drag the finger shaft to follow the motion.
c) Sectional plane A-A: The entrainers fixed to the finger shaft cause finger rotation during the opening of the hand. On the contrary, when the hand closes, the the fingers drive the entrainers.

harness of below-elbow amputees. Secondly, the cable force required to operate the thumb's movement depends on the distance between the mounting of the control cable on the thumb and the center of rotation of the ball joint. The further away from the ball joint's center of rotation it is attached, the bigger the lever the control cable force acts on becomes and thus, reduces the force the amputee has to apply to operate the prosthesis. With the current configuration an acceptable maximum cable force of 120.2 N could be estimated. However, owing to the current location, the control cable will exit the prosthetic cosmesis on the dorsal side of the thumb, which will appear unnatural and be highly conspicuous. Desirably, the control cable is hidden within the cosmesis. This is generally possible by attaching the cable to the thumb guiding pin below the ball joint rather than to the thumb shaft itself. In contrast to the thumb shaft, the thumb guiding pin needs to be pulled in distal direction towards the palm dummy in order to move the thumb towards its open-palm position. Consequently, a deflection pulley is required to ensure, that the cable can still be operated from the proximal direction. Moreover, the distance between the cable attachment and the ball joint's center of rotation is decreased, when shifting the cable below the ball joint, due to a reduced installation space. In order to prevent the required control force from increasing, the force transmission ratio between the control cable force and the pulling force acting on the thumb guiding pin should be alternated. This can be accomplished by utilizing a movable pulley as illustrated in Figure 9 a). Here the cable is fixed to the palm dummy rather than to the thumb itself. To the thumb, in turn, the movable pulley is attached, through which the control cable is guided. A fixed pulley mounted to the palm dummy then redirects the control cable in the desired proximal direction. Due to this configuration, the force, required by the

amputee to operate the system, remains equal despite the decreased distance between cable attachment to the thumb guiding pin and the ball joint's center of rotation.
This is a possible solution, how the control cable attachment can be moved below the ball joint's center of rotation without increasing the cable forces. However, with the presented configuration the cable excursion will increase.

6.2 Potential Finger Mechanic

The fingers of the Michelangelo Hand can adapt to the shape of the object to be grasped. This characteristic is highly desirable in order to increase the grip stability especially when manipulating irregular shaped objects. Recent research focuses on realizing this feature in body-powered VC hands by means of differential coupling. Here the force transmission between adjacent fingers is adapted depending on the forces opposing each finger. As soon as one finger is in contact with an object, further applied force is shifted to the other fingers enabling them to continue flexing. The principle of differential coupling can also be transferred to a VO hand as illustrated in Figure 9 b).
Figure 9 b) shows a VO hand, in which all fingers apart from the thumb are positioned on the same shaft. To this shaft a right-wound cable (green cable) is attached, so that the tensioning of the cable leads to a counterclockwise rotation of the shaft. Thereby it pushes the fingers by means of entrainers (visual in Figure 9 c) sectional plane A-A) to follow its rotational direction, whereas the fingers get extended.
Closing of the hand on the contrary is initiated by a spring. The fingers and the spring are differentially coupled by three floating pulleys each driving a separate tendon (Figure 9 b), yellow cables). When the amputee stops tensioning the control cable, the tension spring pulls the tendons causing the fingers to rotate clockwise. By doing so, the fingers push against the entrainers causing the connecting shaft to follow their movement. However, the transmission of the spring force towards each finger adapts in case a finger contacts an object and hence, cannot rotate any further. Due to changes in the configuration of the pulleys, the other fingers can still continue to rotate clockwise dragging the shaft along.
To couple the movement of the fingers with the thumb movement, the control cable of the shaft and the thumb's control cable merge to a main one, which is attached to the harness. The tensioning of this main control cable causes the finger to rotated counterclockwise in order to extend and the thumb to move towards its open-palm position. When the maximum opening width of the hand has been reached, but the amputee continues to apply a control force, the active grip type of the hand is changed. While doing so, the fingers get slightly hyperextended. In case of the amputee not being satisfied with the finger hyperextending during the change of the grip type, this characteristic could be prevented by incorporating a passive element at the finger cable attachment, which compensates the additional cable tensioning required for the switch of the grip type.

The presented design provides the potential to be equipped with additional features, which could improve its usage even further. For example, it is recommended to incorporate an obstacle, by which the amputee is alerted that the maximum open hand position has been achieved and that the grip type will get switched, when the application of force is continued.

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II

Detailed Design Process

1. Design Goal

The aim of this project was to develop in cooperation with *Otto Bock HealthCare GmbH* a mechanism, which enables to switch between the lateral and an opposition grip of a body-powered prosthesis as easily as with the myoelectric co-contraction. The functionality of the developed mechanism should be proven in practice by means of a functional model.

2. Design Requirements

Deduced from the design goal, the mechanism to be designed needs to promote two main characteristics:

1. a secure selection of a mode
2. the control of the chosen mode in an active manner.

To ensure to develop a device meeting the customers' needs and leading to a successful application, first of all the demands and requirements for the mechanism to be designed were elaborated following the standard procedure of Otto Bock. In this procedure, the design requirements are approached on three levels:

- **Level 1**: The requirements are formulated in a very broad and abstract way.
- **Level 2**: The ideas of the first level are further outlined and specified.
- **Level 3**: It is define in detail, under which exact circumstances the design specifications of the second level are approved to be accomplished.

The defined design specifications are further classified as "must"-, "should"- or "could"-requirements illustrating the importance of the criteria to be implemented in the final design.

Based on the determined and rated requirements conceptual solutions were conceived and finally, evaluated. A concept not fulfilling all design requirements rated as "must", failed to achieve the design goal and hence, it was directly eliminated. "Should"- and "could"-requirements were helpful to rate the different conceptual solutions and to finally choose the one that was most promising for further elaboration.

For the body-powered co-contraction equivalent requirements referring to the function, the control, the user group, the comfort, the appearance, the costs and the transferability of the mechanism had to be determined. The concrete requirements elaborated following Otto Bock's procedure are presented in Table 1. The color coding applied in Table 1 illustrates the classification of the criteria as "must"- (red), "should"- (yellow) or "could"-requirements (green).

Table 1: Design specifications with color coding characterizing the importance of criterion as "must"- (red), "should"- (yellow) and "could"-requirement (green)

	Level 1		Level 2		Level 3	
	No.	Explanation	No.	Explanation	No.	Explanation
Function	100	With the mechanism the grip type must be changeable				
			110	With the mechanism a lateral and an opposition grip must be achievable		
					111	The lateral and the opposition grip must either be VO or VC
					112	The lateral and the opposition grip could be switched between being VO and VC
					113	The movement into the lateral and the opposition grip should appear natural
					114	The thumb positions achieved with the mechanism should match the positions of he Michelangelo thumb for the corresponding grip within a limit ± 5°
					115	The hand opening width should reach at least 80 mm
					116	With the mechanism a pinch force of ≥ 20 N should be achievable in the lateral and in the opposition grip
			120	With the mechanism grip types with the thumb in any position of the circumduction movement of a phyisological thumb could be conducted		
Control	200	The mechanism must be controlled by body motion(s)				
			210	The mechanism must be activated by body motion(s)		
			220	The mechanism should be controlled with a harness		
					221	The mechanism could be controlled with Otto Bock's bandage 21A36=1 for below-elbow amputees
					222	Any changes required to the harness should prevent the user and his/her clothing from any damages

Continuation of Table 1: Design specifications with color coding characterizing the importance of criterion as "must"- (red), "should"- (yellow) and "could"-requirement (green)

	Level 1		Level 2		Level 3	
	No.	Explanation	No.	Explanation	No.	Explanation
User Group	300	The mechanism must be usable by unilateral below-elbow amputees				
			310	The mechanism should be controlled with a reasonable amount of force		
					311	The mechanism should be manipulated with a tension force of ≤ 140 N
			320	The mechanism should be controlled with reasonable amount of cable excursion		
					321	The mechanism should be manipulated with a cable excursion of ≤ 53 mm
	400	The mechanism could be used by bilateral below-elbow amputees				
	500	The mechanism could be used by below-elbow and by above-elbow amputees				
Comfort	600	The usage of the mechanism should be comfortable				
			610	The mechanism should have a low mass		
					611	The mass of the mechanism should be ≤ 207 g
			620	The usage of the mechanism should be as little fatigues as possible		
					621	In case the mechanism requires a permanently applied force, the tension force should be ≤ 25 N
			630	The usage of the mechanism could be as little mentally challenging as possible		
			640	The usage of the mechanism could be intuitive		
			650	After having changed the grip type the control cable should move back to its default state		
					651	After having changed the grip type the control cable should deviate ≤ 4 mm from its default state

Continuation of Table 1: Design specifications with color coding characterizing the importance of criterion as "must"- (red), "should"- (yellow) and "could"-requirement (green)

	Level 1		Level 2		Level 3	
	No.	Explanation	No.	Explanation	No.	Explanation
					652	After having changed the grip type the prostheses must be usable without readjusting the harness
Appearance	700	The mechanism should be inconspicuous				
			710	The mechanism should be visually inconspicuous		
					711	The height the mechanism adds to the size of a standard prosthesis should be ≤ 18 mm
			720	The mechanism should be acoustically inconspicuous		
					721	The acoustic level of the mechanism should be ≤ 35 dB
Cost	800	The manufacturing costs of the mechanism should be ≤ 75 €				
Robustness	900	The mechanism should be robust				
			910	The mechanism should be durable for ≥ 5 years		
					911	The mechanism should survive ≥ 500,000 test cycles of switching the grip type and grasping with the max. achievable pinch force
			920	The mechanism should be temperature-resistant		
					921	The mechanism should be resistant to temperatures between -20°C and +60°C
Transferability	1,00	The mechanism could be adapted to be used as an altering mechanism between different movements (e.g. pronation/supination and gripping)				

In order to reason some requirements and/or a magnitude, which is aimed for, the design specifications are presented again as they were described in the scientific paper.

1. **Function**: The mechanism must promote switching between a lateral and an opposition grip. During the change of the grip type the thumb motion should appear natural. Because of Otto Bock's Michelangelo Hand serving as a model for the final hand design, the thumb positions achieved with the designed mechanism should match the thumb positions of the Michelangelo Hand for the corresponding grip within a limit of $\pm 5°$.
   Commercially available body-powered prostheses can solely promote either active hand opening or hand closing. Depending on which prehension movement the device supports, it is characterized as voluntary opening (VO) or voluntary closing (VC). In case of a VO prosthesis the amputee opens the hand by tensioning the control cable. As soon as the force acting on the cable is released, hand closing is conducted passively by means of supporting elements such as springs or elastics. VC devices work vice versa [1]. Comparable to commercially available prostheses the mechanism must either be VO or VC; ideally, it could support both prehension movements simultaneously or a switch between both modes and hence enable a two-way control.
   To ensure usability of the hand in everyday life, the opening width of the design should reach at least 80 mm, so that a large variety of objects (e.g. a paper cup or a water battle) is graspable. The defined maximum opening width is comparable to the ones of commercially available VO hands, which range from 67 mm to 85 mm [2]. To not only be able to wrap the designed device around these objects, but to actually be able to manipulate them, a grip force of at least 20 N should be achievable in both grip types [2, 3].

2. **Control**: Since the goal of this project is to design a body-powered prosthesis, the mechanism must be controlled and activated by body motion(s). The device should be operated with a harness - ideally it could be controlled with Otto Bock's standard harness *21A36=1* for below-elbow amputees. If the harness design needs to be adapted, e.g. by adding an additional control cable, changes to the harness should prevent the user and his/her clothes from any damages.

3. **User group**: Unilateral, below-elbow amputees must be capable to operate the mechanism. Consequently, the maximum control force required to manipulate the mechanism should be below 140 N, as derived from measurements conducted by C. L. Taylor [4]. He has revealed, that healthy subjects can apply on average a maximum control force of 280 N by means of arm flexion, which is the common body motion below-elbow amputees apply to operate their device [2–4]. Because of children with congenital defects only being capable of achieving a force, which 1.5-2.0 times lower than the maximum force a healthy child can exert, a similar ratio is assumed for an amputee compared to a healthy subject [5]. Thus, the maximum force to activate the designed mechanism was set to 140 N. The control forces of the ungloved body-powered hooks and hands studied by Smit et al. [2, 3] generally also do not exceed this value. Based on C. L. Taylor's study, the cable excursion should not exceed 53 mm [4].
   Ideally, the mechanism could also be operated by bilateral or above-elbow amputees.

4. **Comfort**: The usage of the mechanism should be comfortable. Accordingly, the mechanism should have a low mass of less than 207 g. This magnitude equals the mass of the two motors of the Michelangelo Hand, which will be replaced by the designed mechanism.
   The usage of the mechanism should be as little fatiguing as possible. Therefore, in case of a constant control motion being required to operate the mechanism, the permanently applied force should be less than the critical force of 25.2 N. The critical force describes the force level which can be applied for a prolonged time period without fatigue. It equals around 18% of the maximum force value. With the maximum control force set to 140 N the limit of 25.2 N for a permenantly applied force is derived [3, 6].
   Having changed the grip type, the device must be usable without readjustment of the harness. Moreover, the initial displacements of the control cable in both grip types should only deviate up to 4 mm.

Lastly, the usage of the mechanism could be intuitive and as little mentally challenging as possible[1].

5. **Appearance**: The mechanism should be visually and acoustically inconspicuous. Hence, the mechanism should not add a height of more than 18 mm to the size of a common body-powered prosthesis. This value corresponds to the height batteries used to project from the first generation of myoelectric prostheses. Furthermore, the acoustic level of the working mechanism should be below 35 dB, which is defined as a comfortable acoustic level [7].

6. **Costs**: An adequate sales price was devised with Otto Bock's product manager Simon Marschall, specialized in upper-limb prosthetics. Derived from the estimated sales price, the maximum manufacturing costs should be less than 75 €.

7. **Robustness**: The mechanism should be durable for at least five years. Consequently, the device should survive 500,000 testing cycles of switching the grip type and grasping with the maximally achievable pinch force.
Furthermore, the mechanism should be resistant to temperatures between -20°C and +60°C.

8. **Transferability**: Ideally, the mechanism could be applied to switch between other movements (e.g. wrist pronation/supination and gripping).

In addition to the requirements stated here and in Table 1 respectively, be waterproof and dirt-repellent. Due to these features actually being a characteristic of the cosmesis rather than the mechanic, these latter requirements will not be considered in this project. The listed requirements of little mentally challenging (Table 1 no. 630), intuitiveness (Table 1 no. 640), acoustically inconspicuousness (Table 1 no. 721) and temperature resistance (Table 1 no. 920 & 921) are important characteristics for the final, marketable product. However, in this thesis it was focused on developing the basic functionality of the mechanism, which is why the just mentioned requirements (Table 1 no. 630, 640, 720, 721, 920 & 921) was not considered any further in the design process.

3. Design Approach

Prior to this thesis an extensive literature review was conducted, investigating "Mechanisms to control and alter multiple degrees of freedom of body-powered hand prostheses". In the literature research various attempts to facilitate body-powered hand prostheses with multiple grip patterns (lateral vs. opposition grips or pinch vs. power grips) as well as wrist movements were revealed. The designs encountered served as sources of inspiration to design a mechanism utilizable to change the grip type and to actively control the selected one. In this regard the two way-controlled devices found were highly interesting since they generally comprise a switching mechanism to select between the VO- and the VC-mode. Moreover, the mechanisms of other body-powered devices such as VC-locks, hooks with altering maximum grip strengths or prosthetic elbows, which also contain a locking or switching mechanism, were studied. When thinking outside the box an old light pull switch, a ballpoint pen or a railway switch also present potential solutions how to realize the design goal. To get further inspiration a first round of brainstorming was conducted to come up with additional devices worthwhile considering since they either promote a secure selection of a mode or a locking mechanism. The brainstorming is visualized in Figure 1.

Having studied the concrete mechanisms of these devices, a second round of brainstorming was conducted to conceive, which specific propertiess are required for a mechanism utilized to switch the grip type. Moreover, it was also thought of how these properties can be realized as illustrated in Figure 2.

[1]The design specifications of "being intuitive" and "little mentally challenging" should generally be a "should"- rather than a "could"-requirement. However, due to these characteristics being difficult to evaluate in an objective way, it was decided to implement the two criteria as a "could"-requirement in this thesis.

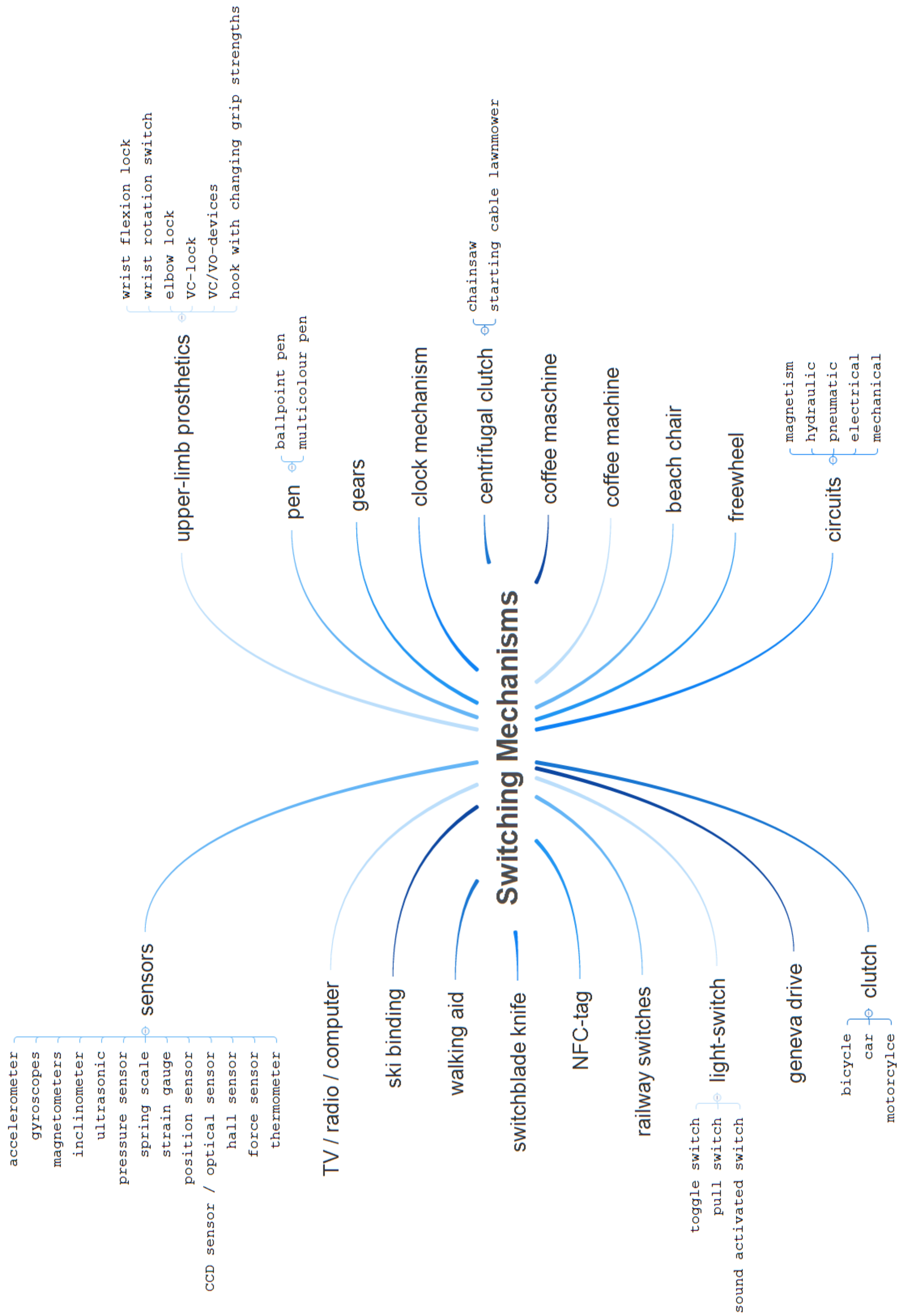


Figure 1: Brainstorming potential sources of inspiration

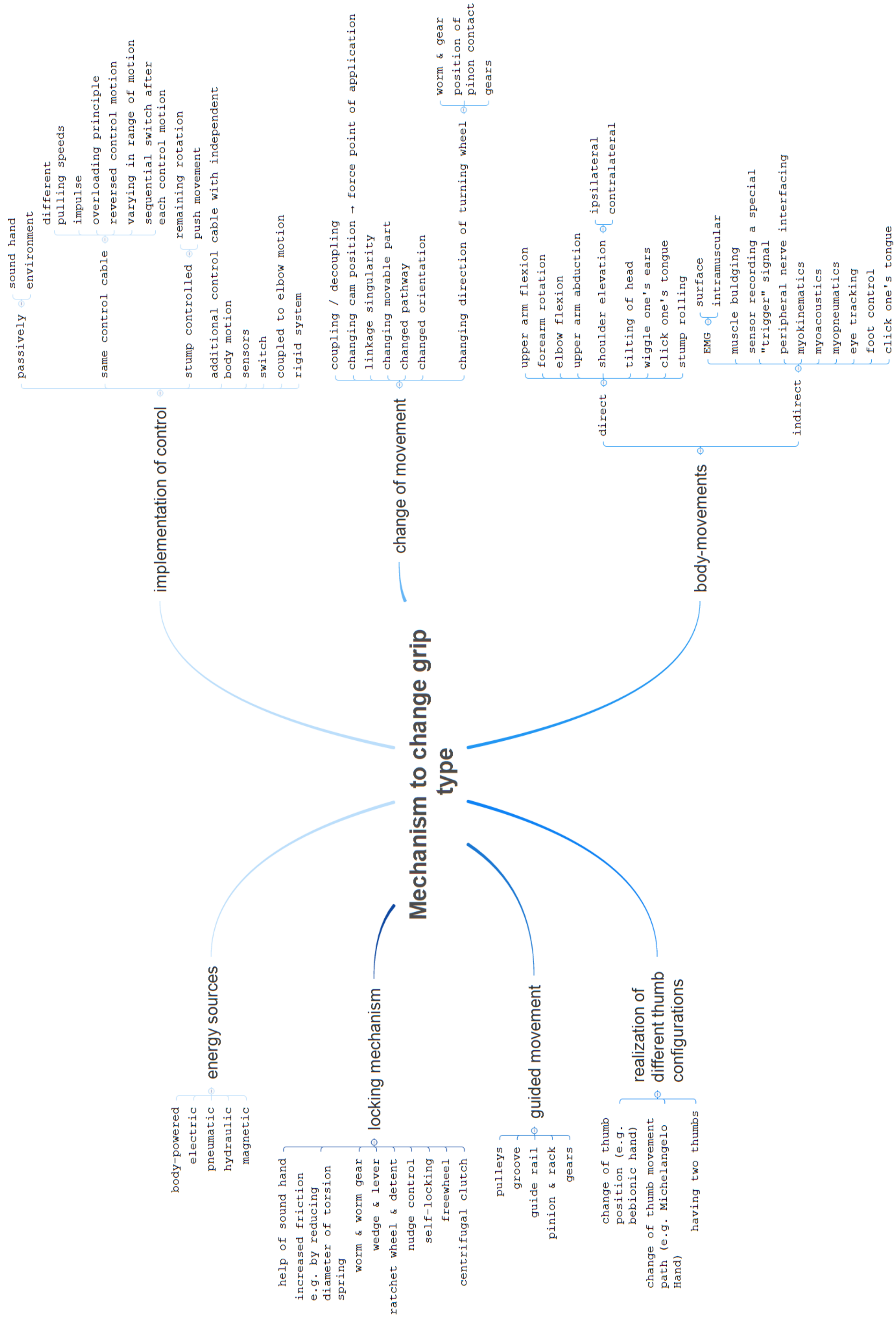


Figure 2: Brainstorming specific properties of the mechanism

For the body-powered co-contraction equivalent the following eight properties were brainstormed to be required to be worked out:

1. **Signal source**: What does initiate the switching operation?
The mechanism is designed to be used for a body-prosthesis and hence, should be operated by body motion(s). However, it can be considered to directly utilize a specific body movement (e.g. ipsilateral forearm flexion) as control input or indirectly by e.g. recording changes in the properties of the muscles when tensioned or by measuring differences in the relative position of adjacent joints.

2. **Control method**: How is the controlling body signal captured and implemented as input to the switching mechanism?
In current body-powered prostheses a Bowden cable connects the terminal device (TD) to a harness, which the amputee wears. By conducting predefined body motions the Bowden cable gets tensioned leading to TD opening or closing. Possibly, this control cable or an additional Bowden cable are used to operate the new mechanism. Other possible solutions are e.g. sensors like accelerometers, gyroscopes or inclinometers, which can record changes in the position of body parts and based on these initiate the operation of the mechanism.

3. **Switch initiation**: How is the switching mechanism triggered?
Similar to the trigger signal in advanced myoelectric prostheses an impulse can be required to provoke mechanism activation. Alternatively, the grip can vary depending on the pulling speed on the cable, in the range of body-motion or by passing a threshold. Moreover, the grip type can change sequentially, so that each time the hand was operated the grip pattern is altered.

4. **Switching mechanisms**: How is the switching realized?
A switching can be implemented by changing the position, orientation or movement direction of a component for example by altering the force point of application or by varying the coupling between parts.

5. **Realization of different grip types**: How does the switching effect the thumb?
In *Steeper*'s myoelectric bebionic hand the amputee can variate between a lateral and an opposition grip by shifting the thumb to the corresponding position [8]. On the contrary, if the amputee co-contracts his/her muscles to initiate a grip switch utilizing a *Otto Bock*'s Michelangelo Hand, the closing pathway of the thumb is changed for the next hand closing motion. Apart from these examples a different grip can also be realized by solely changing the orientation of the thumb; for this the thumb is fixed in position and solely rotates around its longitudinal axis when the grip type is varied.

6. **Securing mode**: How can the selection of the mode be ensured?
To prevent the chosen configuration of the system from being changed arbitrarily, the movable components can be blocked by e.g. positioning a obstacle in the moving pathway of a component, putting a wedge into a gear, a hook catching a cam, a ball detent pressing against a notch or closing valves in a hydraulic system. Furthermore, an increased friction caused e.g. by reducing the diameter of torsion springs or decoupling of components are other possibilities how motion can be inhibited.

7. **Energy source**: How is the gripping actuated?
Commercially available body-powered prosthesis are controlled and driven by the amputee's muscle force. However, it is also possible, that the body motion(s) initiate(s) an battery driven motor, a pump or a pneumatic cylinder, which in turn actuate the grasping motion.

8. **Gripping mode**: How is the prehensional movement conducted?
Comparable to currently available body-powered prostheses, either the opening or the closing of the hand can be operated voluntarily. The reversed motion is conducted passively by means of springs or elastics. Ideally, the VO- and the VC-control can be combined leading to a two-way control.

The ideas, emerged from the second round of brainstorming, were used as inputs to construct a morphological scheme. At this, the eight elaborated properties served as column headings. The morphological scheme is displayed in Figure 2.

Table 2: Morphological scheme

Signal source	**Control method**	**Switch initiation**	**Switching mechanism**	**Realization of different grips**	**Securing mode**	**Energy source**	**Gripping mode**
Stump/ forearm rotation	Same control cable	Default/ secondary state	Change of movement direction	Changing initial thumb position	Changing position/ distance	Body-powered	VO
Ipsilateral shoulder elevation	Additional control cable	Passing threshold	Changing moving pathway	Changing opening/ closing pathway	Wedging/ blocking	Electric	VC
Contralateral shoulder elevation	Sensor	Varying in rage of motion	Changing position/ distance	Having two thumbs in different positions	Increased friction/ preventing movement	Pneumatic	VO/VC
Upper arm flexion	Rigid system	Different pulling speed	Changing movable part			Hydraulic	
Upper arm abduction	Switch	Impulse	Changing orientation			Magnetic	
Elbow flexion		Reversed motion	Linkage singularity				
Lower extremities		Sequential	De-/ coupling				
Butt cheeks movement		Manual					
Head movements							
Sound hand							
Myopneumatics							
Muscle buldging							
Myoacoustics							
EMG							
Stump rolling							

By combining characteristics of different columns a great variety of possible conceptual solutions for the body-powered co-contraction equivalent were conceived as visualized in Figure 3. For example a hybrid prosthesis could be designed, in which the grip type variation is triggered by myoelectric signals. Alternatively, the buldging of a muscle, when it gets contracted, could initiate the thumb to change its orientation. On the contrary, thumb position switching could be coupled to e.g. stump rotation, elbow flexion or internal shoulder rotation.

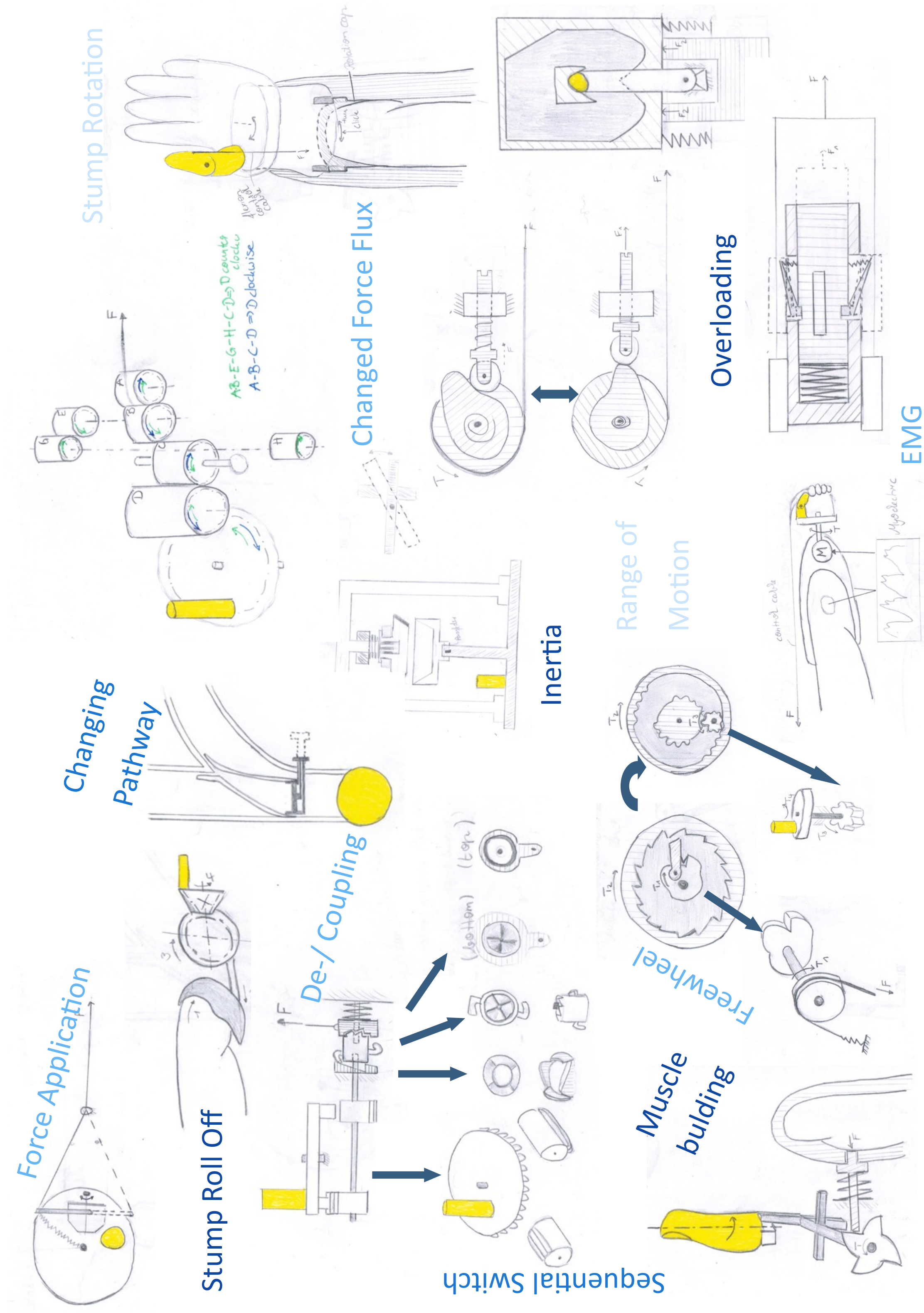


Figure 3: Design variety

It becomes evident, that the mechanism can be realized in very diverse ways. To narrow the numbers of possibilities, additional determinations were established under discussion with Thomas Bertels and Lukas Brünjes as specialists in the field of body-powered upper-limb prostheses at Otto Bock. In this connection the following characteristics were specified:

- Do not design a hybrid device, because in this way the body-powered advantages of lightweight, low cost and independence of an external energy source will be removed. Moreover, it would not present an actual body-powered alternative to the Michelangelo Hand.
- Do not develop a mechatronic system since electrical components are more prone to damage, more expensive and require an external energy source. Consequently, not all advantages of a body-powered prosthesis would be exploited, when adding electrical parts.
- Discard the idea of (mechanical) sensors to keep the amputee as the input source of the control cycle.
- Design a purely mechanical system due to the company's expertise in developing and manufacturing purely mechanical body-powered prostheses.
- Design the system in such a way, that the switching can be applied without requiring neither an assistant object nor the sound hand in order to ensure the possibility of switching the grip type at any point.

To also have the view of the prosthesis user represented in the design process, the orthopedic technician Dieter Storck, Otto Bock's specialist in patient care with body-powered prostheses, was interviewed. He emphasized, that the control of the mechanism should not tremendously differ from the current harness principle since patients, accustomed to the current body-powered prostheses, will hardly adapt to a completely new control mechanism. Moreover, he advised to ensure a big range of amputees being capable to use the new mechanism. Consequently, stump rotation should not be consideredany further since only below-elbow amputees with a remaining stump length of 12.7 cm or longer are still capable of it [4]. Additionally, it became apparent, that adding an extra control cable for the change of the grip type is impractical since the independent operation of numerous cables bears a big mental challenge for the user. This especially refers to above-elbow amputees, who already have to operate two different cables.
Derived from the discussion with Dieter Storck, the change of grip type should ideally be operable with the already existing control cable.

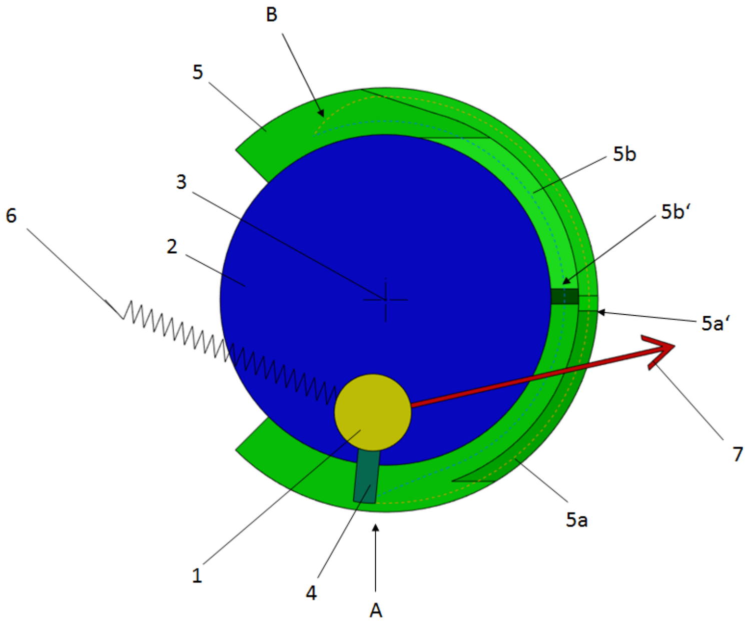
Step-by-step the idea emerged to trigger the switching of the grip type by overloading the system: when a VO hand is fully opened, additional force applied to the control cable will initiate the change of grip type. Conceptual solutions based on this overloading principle were developed and will be depicted in the following Section 4.

4. Conceptual Solutions

Six concepts were designed based on this overloading principe. Their specific functional principles will be explained hereinafter by means of a 2D conceptual drawing and a detailed description. Here the change from a lateral to an opposition grip is considered. To provide a clearer understanding of the concepts 3D illustrations of the solutions will be presented as well.

Alternative 1

Functional Principle



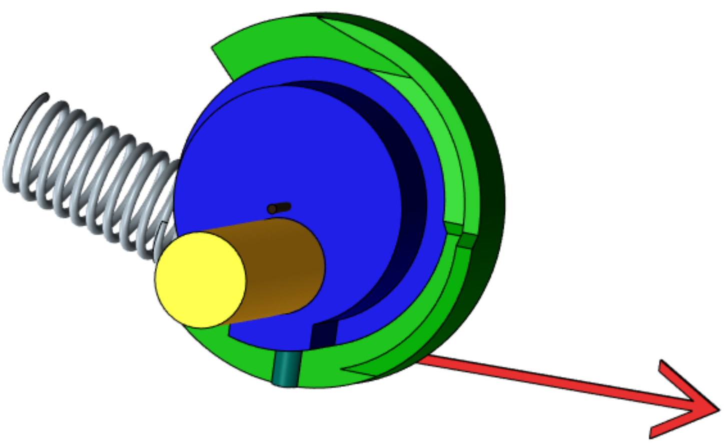
Components

- Thumb dummy (1)
- Rotating plate (2), on which thumb dummy (1) is eccentrically positioned on, with rotational axis (3)
- Movable pin (4); pin (4) can be changed in vertical direction and it can be pushed in; pin (4) is coupled to rotating plate (2) and hence, follows its rotational movement
- Stationary guideway (5) with two pathways (5a/5b) with distinct elevation profiles:
  - Posterior pathway (5a) with high elevation profile and pathway maximum (5a')
  - Anterior pathway (5b) with low elevation profile and pathway maximum (5b')

  The pathways (5a/5b) intersect at the two turning points (A/B):
  - Turning point (A) causes the lateral position of the thumb (configuration is drawn)
  - Turning point (B) causes the opposition end position of the thumb

  Pin (4) contacts the stationary guideway (5)and is hence affected by its elevation profiles
- Retraction spring (6)
- Control force (7)

CAD

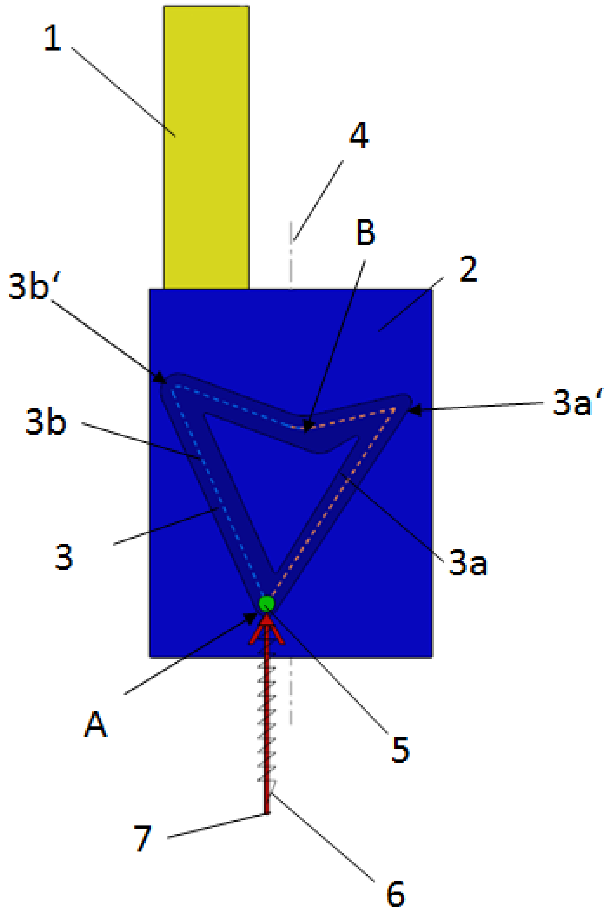


Description

- The thumb dummy (1) is initially located in its lateral position and hence the pin (4) coincides with the turning point (A).
- When the control force (7) is applied to the rotating plate (2), on which thumb dummy (1) is eccentrically positioned on, the two components are caused to pivot counterclockwise. Through this rotation the hand get opened.
- The pin (4) is mounted to the rotating plate (2) as well, which is why it is dragged along to move counterclockwise. Since the pin (4) contacts the stationary guideway (5), its specific movement trajectory is effected by the specific elevation profiles of the two pathways (5a/5b) of the stationary guideway (5).
- Starting from the lateral position (A) the pin is directed to follow the posterior pathway (5a). Thereby it gets lifted until the posterior pathway maximum (5a').
- As long as the control force (7) only causes such a rotational movement of rotating plate (2) and movable pin (4) to reach the posterior pathway maximum (5a'), the retraction spring (6) moves the system back to the starting position (A).
- As soon as the control force (7) causes the movable pin (4) to pass the posterior pathway maximum (5a'), the retraction spring (6) changes orientation and hence, continues to drive the rotating plate (2) counterclockwise until the movable pin (4) reaches turning point (B). Then thumb dummy (1) has reached its opposition position and the hand is closed.
- With the change of the thumb dummy (1) from its lateral to its opposition position, the control force point of application is mirrored as well. Hence, the control force (7) applied from the same pulling direction as before will now cause the rotation plate (2) and the coupled components to rotate clockwise, whereby the hand gets opened again.
- Due to the specific elevation profile of the two pathways (5a/5b) of the stationary guideway (5), the pin (4) is this time directed to follow the anterior pathway (5b) . For this, the movable pin (4) gets pushed in by the wall of the stationary guideway (5).
- As long as the applied force (7) only causes a rotational movement of rotating plate (2) and movable pin (4) until the anterior pathway maximum (5b'), the retraction spring (6) moves the system back to the position (B).
- As soon as the applied force (7) causes the movable pin (4) to pass the anterior pathway maximum (5b'), the retraction spring (6) changes orientation and hence, drives rotating plate (2) to turn clockwise until the pin (4) reaches turning point (A); the thumb dummy (1) has been moved back to its lateral position.

Alternative 2

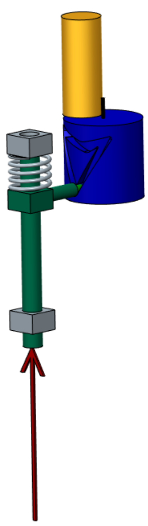
Functional Principle



Components

- Thumb dummy (1)
- Cylinder (2) with heart curve (3) pivoted around axis (4); thumb dummy (1) is eccentrically positioned on the cylinder (2); heart curve (3) comprises two pathway branches (3a/3b) each with a maximum (3a'/3b') and with a resting position (A/B):
  - Resting position (A) keeps the thumb dummy in its lateral position(configuration is drawn)
  - Resting position (B) keeps the thumb dummy in opposition
- Pin (5), which is guided within heart curve (3) and has retraction spring (6) attached
- Control force (7)

CAD



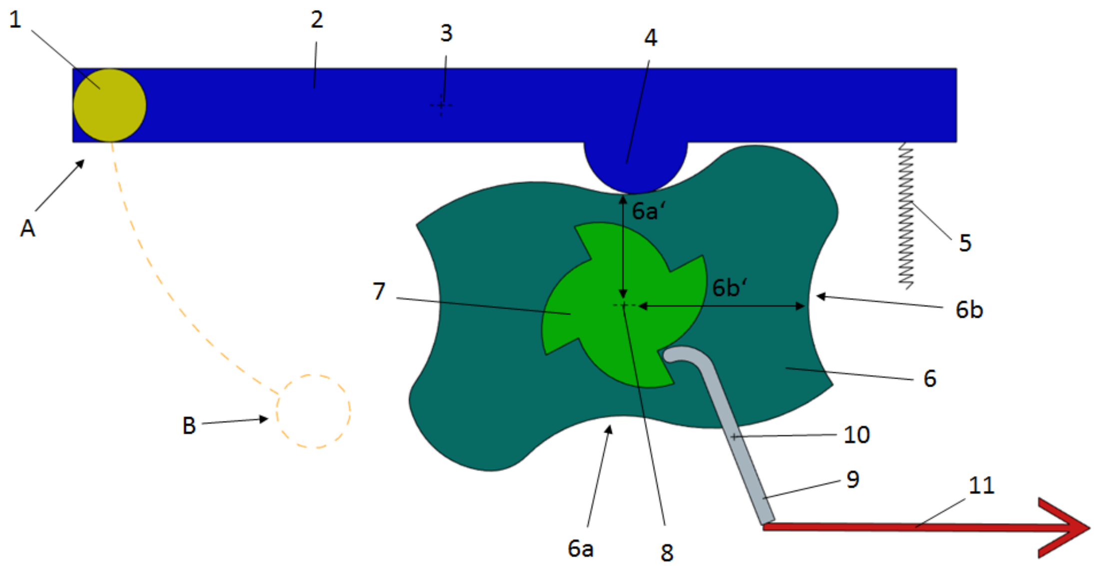
Description

- When the thumb dummy (1) is located in its lateral position, the pin (5) is positioned in the resting position (A) of heart curve (3).
- When the control force (7) is applied to the pin (5), it pushes the pin (5) upwards.
- Pin (5), in turn, acts on the inclined wall of the pathway branch (3a) of the heart curve (3) causing a counterclockwise rotation of the cylinder (2) and the mounted thumb dummy (1). Through this rotation the hand is opened.
- As long as the control force (7) causes the pin (5) to move within pathway (3a) solely until its maximum (3a'), the retraction spring (6) drags pin (5) back to its starting position (A) in case of force (7) release. Consequently, a lateral grasp is achieved.
- If the control force (7) causes the pin (5) to pass the maximum (3a') of pathway branch (3a), the retraction spring (6) moves the pin (5) to the other the resting position (B) as soon as the force (7) is stopped resulting in an opposition grip.
- When the control force (7) is applied another time, the pin (5) follows pathway branch (3b) causing a counterclockwise rotation of the cylinder (2) with thumb dummy (1). Hence the hand is opened again.
- As long as pin (5) is solely moved up to the maximum (3b') of the pathway (3b), the release of the control force (7) always leads to an opposition grip.
- If the pin (5) has been moved past the maximum (3b') of the pathway branch (3b), the retraction spring (6) pulls the pin (5) back to the initial resting position (A), which equals the lateral position of the thumb dummy (1).

  pin (5) will be moved to the original resting position (A), which equals the lateral position of thumb (1)

Alternative 3

Functional Principle



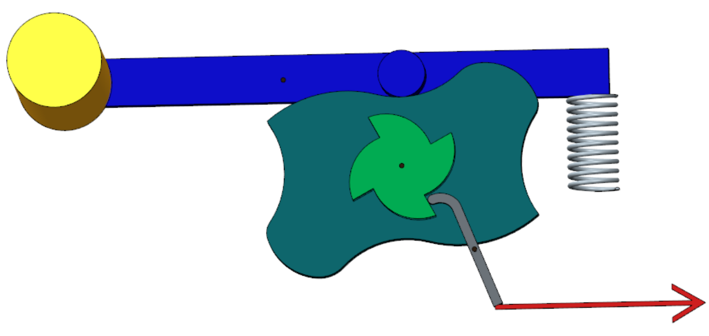
Components

- Thumb dummy (1)
- Thumb lever (2) with bulge (3) pivoted around axis (4); thumb dummy (1) is positioned on one end of lever (2) and retraction spring (5) is attached to the other end
- Positioning plate (6) pivoted around shaft (8) with the following characteristics:
  - Opposing sides of positioning plate (6) have the same curvature
  - Each side comprises a indentation, leading to two different kinds of indentations (6a/6b), in which bulge (3) gets alternately positioned in
  - The distance (6a′) between the minima of the indentation type (6a) to shaft (8) is smaller than the distance (6b′) between the minima of the indentation type (6b) to shaft (8)

  With the positioning plate (6) two different orientations of thumb lever (2) are achieved depending on in which the indentation type (6a/6b) bulge (3) is positioned in. Consequently, the thumb dummy (1) is switched between to end positions (A/B):

  - When bulge (3) is positioned in indentation type (6a) (drawn), the thumb lever (2) is orientated horizontally with thumb (1) located in position (A), which resembles the lateral grip.
  - When bulge (3) is positioned in indentation type (6b), the right lever arm of thumb lever (2) is pushed up leading to the left lever arm of thumb lever (2) with thumb (1) being tilted. As a result, thumb (1) is moved to its second position (B), which resembles the opposition grip.
- Ratchet wheel (7), which is coupled to positioning plate (6) by means of shaft (8)
- Positioning lever (9) rotatably mounted around axis (10)
- Control force (11)

CAD

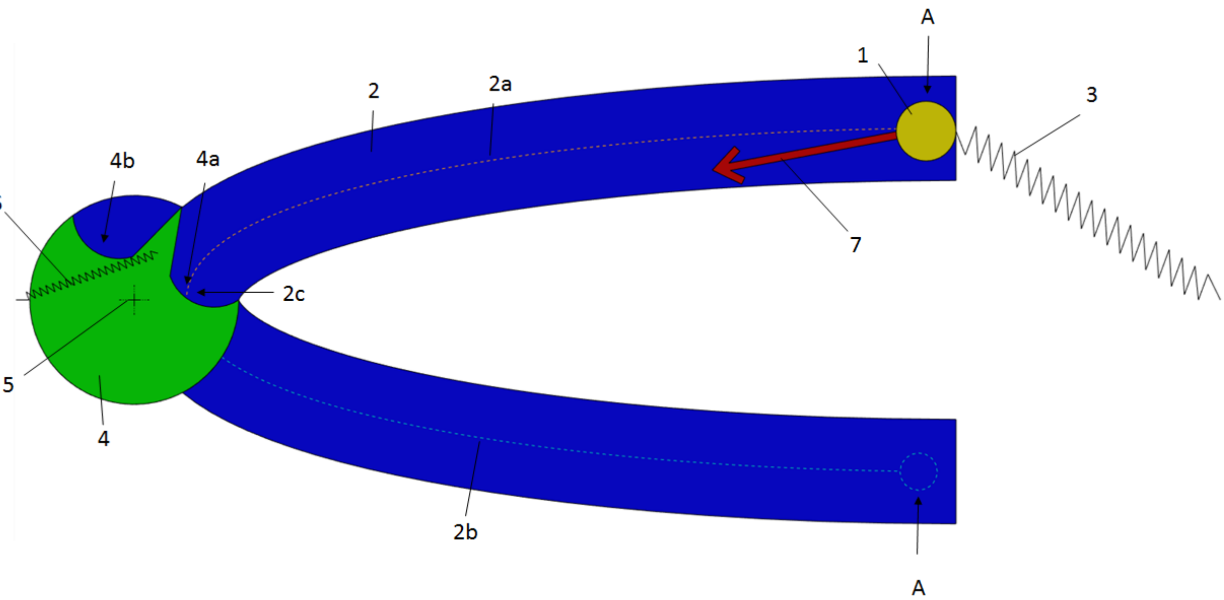


Description

- When conducting a lateral grip, the thumb dummy (1) is located in the position (A), the thumb lever (2) is horizontally orientated with bulge (3) positioned in indentation type (6a) of positioning plate (6).
- When a control force (11) is applied to the distal arm of positioning lever (9), the proximal lever arm pushes against a wall of the ratchet wheel (7) causing it to rotate clockwise about 90°.
- Since the ratchet wheel (7) and the positioning plate (6) are coupled by shaft (8), the positioning plate (6) follows the clockwise rotation about 90° of ratchet wheel (7).
- When positioning plate (6) rotates about 90° clockwisely, its curvature causes bulge (3) first to be pushed up and finally to be guided to the other indentation type (6b).
- Because of the distance (6b') between indentation type (6b) to shaft (8) being bigger than the distance (6a') between the indentation type (6a) and the shaft (8), the right lever arm of thumb lever (2) is pushed upwards and kept in this position. Consequently, the left lever arm of thumb lever (2) is tilted in such a way, that thumb dummy (1) reaches its second position (B). Thus, an opposition grip is achieved.
- When the control force (11) stops, the positioning lever (9) rotates back to its default state. Here its proximal lever arm slides over the curvature of the ratchet wheel (7) until it reaches a straight surface. Hence, the system is prepared for a following switching procedure.
- Each time the magnitude of force (11) is sufficient to rotate the ratchet wheel (7) about 90°, the bulge (3) gets alternatively positioned in indentation type (6b) and (6a):
  - If bulge (3) is positioned in indentation type (6b), thumb lever (2) is kept in the tilted position causing thumb dummy (1) to be located in position (B), by which an opposition grip is achieved.
  - If bulge (3) is positioned in indentation type (6a), thumb lever (2) is kept horizontally causing thumb dummy (1) to be arranged in position (A). In this way a lateral grip is achieved.
- Retraction spring (5)supports buldge (3) to move from indentation type (6b) to the lower positioned indentation type (6a) by pulling the thumb lever (2) back to its horizontall position.

Alternative 4

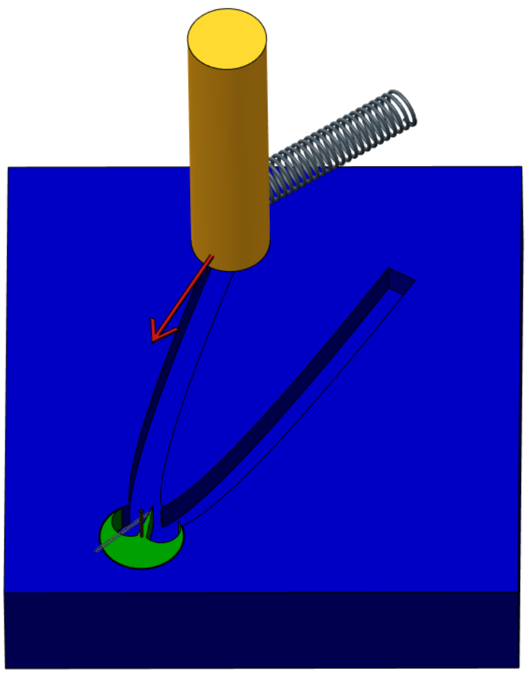
Functional Principle



Components

- Thumb dummy (1)
- Stationary parabolic pathway (2) with the two parabola branches (2a / 2b), the apex (2c) and the two end positions (A/B)
  - End position A equals the lateral end position of the thumb (thumb is drawn in this position)
  - End position B equals the opposition end position of the thumb
- Thumb retraction spring (3)
- Toggle (4) positioned in the apex (2c) of the parabolic pathway (2) and pivoted around axis (5); moreover, toggle (4) comprises two notches (4a / 4b)
- Toggle spring (6)
- Control force (7)

CAD

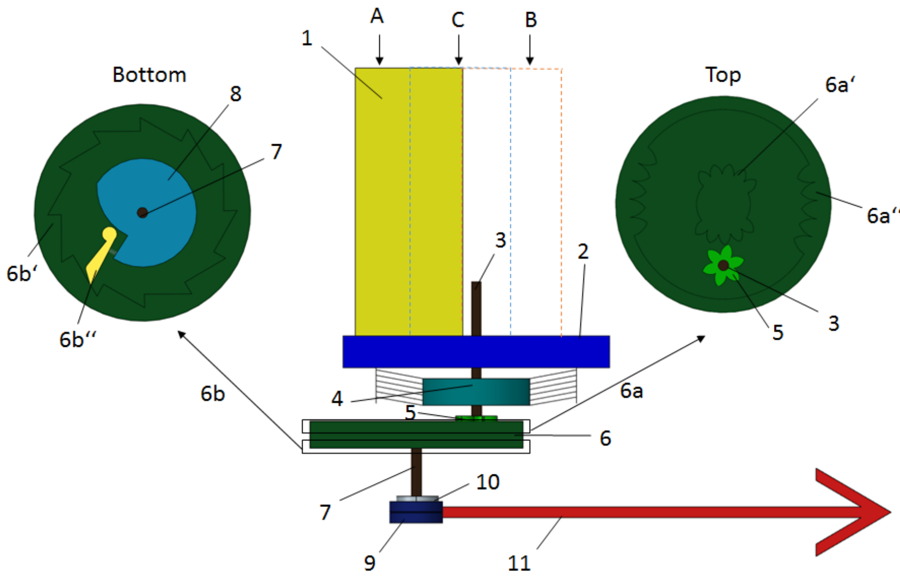


Description

- The control force (7) applied to thumb dummy (1) causes thumb movement towards the apex (2c) of pathway (2) and hence, hand opening.
- Due to the starting position (A) the thumb dummy (1) is moved within branch (2a) until the parabola apex (2c), which corresponds to the maximum hand opening width.
- The retraction spring (3) is tensioned proportional to the hand opening width.
- The thumb dummy (1) is always pulled back by the retraction spring (3) to its starting position (A), if the control force (7) is released before the thumb dummy moved beyond apex (2c).
- If the control force (7) promotes thumb dummy (1) to pass parabola apex (2c) and hence, leads to overflexion of the hand, thumb dummy (1) is shifted to the other parabola branch (2a → 2b) by means of toggle (4).
- As soon as thumb dummy (1) reaches the apex (2c) of pathway (2), it is located within notch (4a) of toggle (4).
- When in this configuration additional force (7) is applied to the thumb dummy (1), the thumb dummy (1) pushes against the side wall of notch (4a) and causes clockwise rotation of toggle (4) around the axis (5).
- When the thumb dummy (1) has passed the parabola apex (2c), the orientation of the retraction spring (3) changes.
- Once notch (4a), in which thumb dummy (1) is located in, matches the opposite parabolic branch (2b), thumb dummy (1) is pulled in case of force relief by the retraction spring (3) along parabolic branch (2b) into the other end position (B). Hence, the thumb dummy (1) is now located in its opposition end position.
- Toggle spring (6) ensures, that the toggle (4) is rotated into its second end position, in which notch (4b) coincides with parabola branch (2b), in order to be prepared for an other thumb position variation.
- The switching procedure from the thumb's opposition to its lateral end position is comparable.

Alternative 5

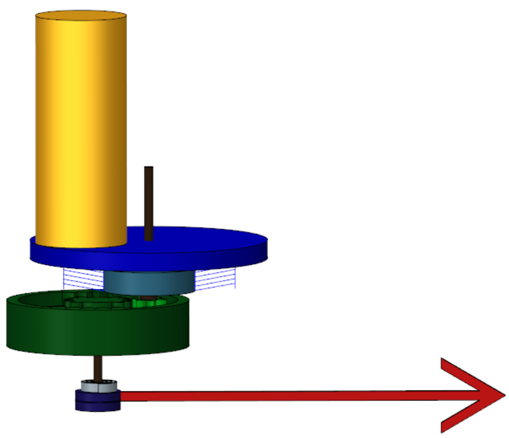
Functional Principle



Components

- Thumb dummy (1)
- Rotating plate (2), on which thumb dummy (1) is eccentrically positioned on, with shaft (3); rotating plate (2) moves the thumb dummy (1) between to end positions (A/B):
  - End position (A) equals the lateral position of the thumb (configuration is drawn)
  - End position (B) equals the opposition position of the thumb
  - Midway (C) between end position (A) and end position (B) symbolizes the open-palm grip, in which the hand is maximally opened
- Encastré plate (4)
- Stationary thumb pinion (5)
- Wheel (6) rotatable around shaft (7) with gearing on its top side (6a) and freewheel on its bottom side (6b):
  - Top side (6a) has alternately center (6a’) and ring (6a”) gearing
  - Bottom side (6b) comprises a ratchet freewheel with ring gear (6b’) and detent (6b”).
- Driving plate (8), to which detent (6b”) is mounted to, is coupled to plate (9) by means of shaft (7)
- Torsion spring (10) attached to plate (9)
- Control force (11)

CAD

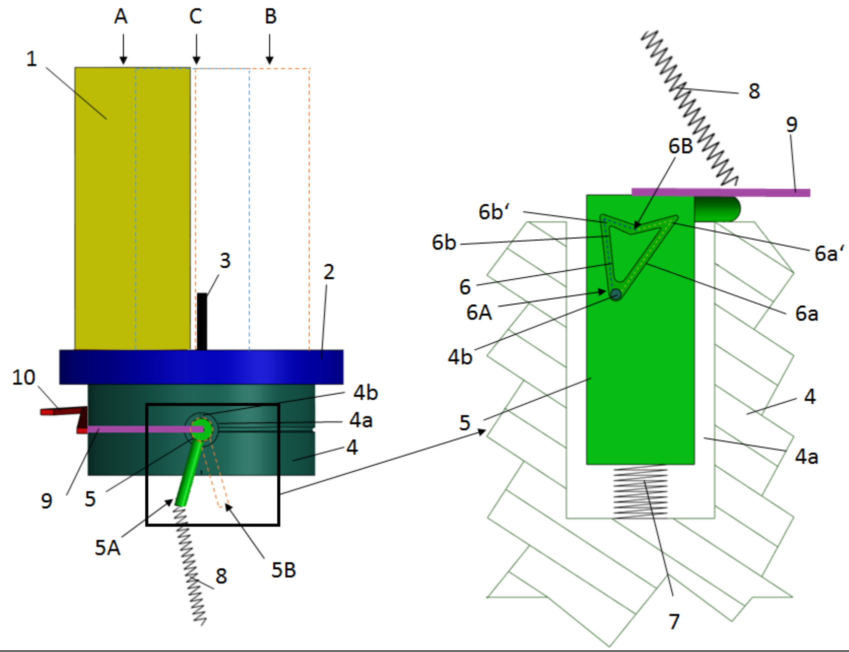


Description

- The control force (11) applied to the plate (9) causes clockwise rotation of it and of the shaft (7), by which torsion spring (10) gets loaded.
- Because of driving plate (8) being coupled to plate (9) by means of shaft (7), it follows the clockwise rotation of plate (9).
- When the driving plate (8) is rotated clockwise, the attached detent (6b″) engages in a recess of the ring gear (6b′) causing the wheel (6) to follow the movement.
- In contrast, when driving plate (8) rotates counterclockwise, detent (6b″) solely slides over the cogs of ring gear (6b′). Consequently, wheel (6) does not get coupled to driving plate (8) and hence, rests in its position. This is the case, when the control force (11) is released. The preloaded torsion spring (10) rotates plate (9) and driving plate (8) back to their default state without effecting wheel (6). Consequently, wheel (6) keeps its last achieved position.
- When the control force (11) is applied and hence, turns plate (9) and driving plate (8) to rotate clockwise, wheel (6) is set into motion due to the actions on its distal side (6b). Du to gearings (6a′ /6a″) on its proximal side (6a) the rotating wheel (6) actuates the thumb pinion (5) to.
- The thumb pinion (5) turns, because any translational movements are prevented by the encastré plate (4).
- The rotational direction of pinion (5) depends on the pinion (5) meshing either with the center gearing (6a′) or with the ring gearing (6a″).
- Rotating plate (2), on which thumb dummy (1) is eccentrically positioned on, is coupled to the thumb pinion (5) by means of shaft (3). Hence, both components follow the rotation of pinion (5).
- Starting with the thumb dummy(1) in its lateral end position (A) the pinion (5) is about to engage with the center gearing (6a′).
- Clockwise rotation of wheel (6) causes pinion (5) to pivot counterclockwise.
- The rotating plate (2) and consequently, thumb dummy (1) follow this rotational movement, which leads to the thumb being moved from its lateral end position (A) towards the open-palm position (C).
- If the force application continues, the thumb will be rotated further in counterclockwise direction until the thumb reaches its opposition end position (B),since pinion (5) was still engaged to the center gearing (6a′).
- As soon as the control force is released, the thumb dummy (1) will keep the position, it just reached. Here it will stay in its opposition end position (B).
- If the control force is continued or applied for an other time, pinion (5) will start to mesh with the upcoming ring gearing (6a″) leading to a clockwise rotation. Consequently, thumb dummy (1) will be rotated from its opposition end position (B) towards its lateral end position (A), by which it first moves towards the open-palm position (C).
- In case of the force (11) stopping before the thumb reaches the lateral end position (A), the thumb dummy (1) rests in the just achieved position until another force (11) is applied. Then, it is again rotated counterclockwise towards the lateral end position (A).
- When the thumb (1) is moved towards the open-palm position (C), the hand is controlled in VO-mode; e.g. in case of movement from the lateral (A) to the opposition end position (B): the hand is controlled VO when the thumb is moved from the lateral end position (A) to the open-palm position (C) (A→ C).
- As soon as the thumb (1) passes the open-palm position (C), the prehension mode gets switched into VC; e.g. in case of movement from the lateral (A) to the opposition end position (B): the hand is controlled VC from the open-palm position (C) to the opposition end position (C) (C → B).

Alternative 6

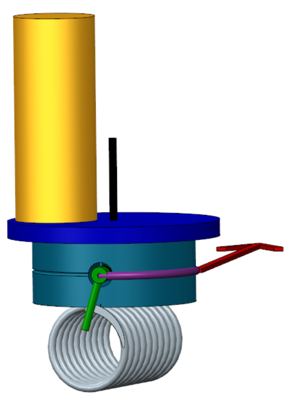
Functional Principle



Components

- Thumb dummy (1)
- Rotating plate (2), on which thumb dummy (1) is eccentrically positioned on, with shaft (3); the rotating plate moves thumb dummy (1) between two end positions (A/B):
  - Position (A) equals the lateral end position (configuration is drawn)
  - Position (B) equals opposition end position
- Positioning wheel (4) with bore (4a) and guiding pin (4b)
- Positioning pin (5) is located withing bore (4a) of positioning wheel (4) and comprises a heart curve (6), in which guiding pin (4b) of positioning wheel (4) positioned. Depending on the position of guiding pin (4b) within heart curve (6), positioning pin (5) is turned off center to its left/right orientation (5A/5B). This in turn effects the thumb position (A/B):
  - When guiding pin (4b) is positioned at heart curve's resting position (6A), positioning pin (5) is rotated to orientation (5A) holding thumb dummy in position (A) (drawn)
  - When guiding pin (4b) is positioned at heart curve's resting position (6B), positioning pin (5) is rotated to orientation (5B) holding thumb dummy in position (B)
- Pin spring (7) is attached to bottom of positioning pin (5)
- Retraction spring (8) is mounted to positioning pin (5) and changes orientation depending on the orientation (5A/5B) of positioning pin (5)
- Cable (9) (here: left-)wound around positioning wheel (4)
- Control force (10)

CAD



Description

- The lateral position (A) of thumb dummy (1) is achieved by guiding pin (4b) being located in the heart curve's resting position (6A); hence it shifts positioning pin (5) and the attached retraction spring (8) to their left orientation (5A).
- The control force (10) applied to the left-wound cable (9) causes a clockwise rotation of positioning wheel (4) and the coupled rotating plate (2). Hence, thumb dummy (1) is moved in clockwise direction to its open-palm position (C), at what cable (9) is fully unwound.
- Through the rotation of the positioning wheel (4), the retraction spring (8) gets tensioned.
- When the control force (10) is then released, the preloaded retraction spring (8) drags positioning wheel (4) to rotate counterclockwise. By this thumb dummy (1) is moved back to its initial position (A).
- When the control force (10) application is continued even though control cable (9) is fully unwound, the positioning pin (5) is pulled out of the bore (4a).
- Hereby the guiding pin (4b) moves within the heart curve pathway (6a) causing a counterclockwise rotation of positioning pin (5).
- When the guiding pin (4b) has reached the heart curve maximum (6a'), it is directed to the heart curve's resting position (6B) as soon as the control force (10) is released, because the pin spring (7) pulls the positioning pin (5) back into bore (4a).
- When the guiding pin (4b) moves to the resting position (6B) it tuns positioning pin (5) to its right offset (5B). Consequently, the orientation of the retraction spring (8b) has been changed as well.
- Due to the spring (8) having been shifted to the right offset, it now drags the positioning wheel (4) to rotate clockwise, thereby winding cable (9) the other way round as before.
- The reversed movement of positioning wheel (4) causes the thumb dummy (1) to be moved to its opposition end position (B).
- When the control force (10) is then applied to the now right-wound cable (9), the positioning wheel (4) is now rotated counterclockwise, where control cable (9) is unwound. Consequently, the thumb (1) is moved from its opposition grasp position (B) to its open-palm position (C).
- In case the application of the control force (10) stops, when the control cable (9) is fully unwound, the retraction spring (8) will move the thumb dummy (1) back to its opposition grip position (B).
- However, if additional control force (10) is applied to control cable (9) even though it is already fully unwound, positioning pin (5) is pulled out of the bore (4a).
- Hereby the guiding pin (4b) moves alongthe heart curve pathway (6b) causing the positioning pin (5) to rotate clockwise.
- When the guiding pin (4b) has reached the heart curve pathway maximum (6b') and the control force (10) is released, the pin spring (7) pulls the positioning pin (5) back into the bore (4a). Thereby it moves the guiding pin (4b) to the resting position (6A).
- This action causes positioning pin (5) and accordingly, retraction spring (8) to be shifted to their left configuration (5A). Consequently, positioning wheel (4) is turned by retraction spring (8) in counterclockwise direction, by what control cable (9) gets left-wound. Moreover, thumb dummy (1) is moved to its lateral end position (A).

5. Evaluation of Concepts

These six conceptual solutions were compared and analyzed in order to expose the principle, which fulfills the design requirements the best way and hence, bears the highest potential for further elaboration. For this, the design requirements stated in Table 1 were translated into evaluation criteria, which are described in Table 3. Later on the concepts were judged how well they fulfill each of these criteria.

Table 3: Evaluation criteria derived from the design requirements described in Table 1

Evaluation Criterion[1]	**Description**	**No. in Table 1**
VO- & VC Realization	The mechanism enables the prosthetic hand to be controllable in VO- and in VC-mode.	112
Stability of Position	A secure grip can be achieved with the mechanism, so that high opposing forces of an object cannot arbitrarily change the grip selection.	116
Physiological Kinematic	The movement of the thumb during grip variation is as similar to the physiological thumb kinematic as possible.	113, 120
Deviation to Michelangelo Thumb	The position of the thumb during grasping is consistent with the position of the Michelangelo thumb in the corresponding grip type.	114
Opening Width	The hand opening width equals at least 80 mm.	115
Harness Control	The mechanism is controlled by means of a harness.	220, 221
Altering Force	A small force value is required to operate the mechanism.	310, 311, 400, 500, 620, 621
Cable Excursion	The cable excursion required to control the mechanism is small.	320, 321, 400, 500
Light Weight	The mechanism is lightweight [2].	600, 610, 611
Robustness	The mechanism is durable.	900, 910, 911
Cable Deviation	The cable routing after the grip type variation does not deviate from the previous cable routing.	650, 651
Dimensioning	The mechanism can be minimized to fit within the glove of the Michelangelo Hand.	700, 710, 711
Manufacturing Costs	The manufacturing costs of the mechanism are low.	800
Complexity	The mechanic of the mechanism is designed in a simple way.	800, 900
Transferability	The mechanism can easily be transferred to switch between prehension and wrist movements.	1,000

[1] The safety of the patient is generally the first priority for a medical device. Nevertheless, it was not considered as a design criteria since the mechanics of the hand prosthesis will in the end be covered with a glove. Moreover, the requirement no. 222 referring to an additional control cable as a possible source of harm gets redundant since the concepts are based on applying the already existing control cable.

[2] To evaluate the mass of the concepts, the number of components of the concept is considered. The more parts are incorporated in the concept, the higher the mass is estimated.

The design specifications judged as a "must"-requirement (No. 100, 110, 111, 200, 210, 300, 652 in Table 1) were not translated into evaluation criteria, because a concept not fulfill all "must"-requirements would have been directly eliminated.
Each design specification is of different importance to the final product, which can be implemented in the concept evaluation by means of weighting factors. Such weighting factors were determined for each evaluation criteria, presented in Table 3, by means of the "paired comparison"-method as illustrated in Table 4. For this, all evaluation criteria were compared in pairs to each other. If the criterion stated in the row was judged to be less important than the one in the column, it got zero points allocated. One point represents equal importance of the two criteria and two points symbolize

the criteria in the row being more important than the one in the column. By summing up the points in one row and dividing the sum s_i by the total number of points distributed in Table 4 the weighting factor w_i of the criterion stated in the row was calculated [9].

Table 4: "Paired Comparison"-method: The requirement in the row compared to the one in the column is:0 = less important; 1 = equally important; 2 = more important[9]

	VO- & VC Realization	**Stability of Position**	**Physiological Kinematic**	**Deviation to Michelangelo Thumb**	**Opening Width**	**Harness Control**	**Altering Force**	**Cable Excursion**	**Light Weight**	**Robustness**	**Cable Deviation**	**Dimensioning**	**Manufacturing Costs**	**Complexity**	**Transferability**	**Sum s**	**Weighting Factor[1] w [%]**
VO- & VC Realization		0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.48
Stability of Position	2		2	2	2	1	2	2	2	1	2	2	2	2	2	26	12.38
Physiological Kinematic	2	0		1	0	0	0	0	1	0	1	0	1	2	2	10	4.76
Deviation to Michelangelo Thumb	2	0	1		0	0	0	0	1	0	0	0	1	1	0	6	2.86
Opening Width	2	0	2	2		1	1	1	2	0	0	0	2	2	2	17	8.10
Harness Control	2	1	2	2	1		2	1	2	1	1	1	2	2	2	22	10.48
Altering Force	2	0	2	2	1	0		1	2	1	2	1	2	2	2	20	9.52
Cable Excursion	2	0	2	2	1	1	1		1	0	2	2	2	1	2	19	9.05
Light Weight	2	0	1	1	0	0	0	1		1	0	2	1	2	2	13	6.19
Robustness	2	1	2	2	2	1	1	2	1		2	2	2	2	2	24	11.43
Cable Deviation	2	0	1	2	2	1	0	0	2	0		1	1	2	2	16	7.62
Dimensioning	2	0	2	2	2	1	1	0	0	0	1		2	2	2	17	8.10
Manufacturing Costs	2	0	1	1	0	0	0	0	1	0	1	0		1	2	9	4.29
Complexity	2	0	0	1	0	0	0	1	0	0	0	0	1		2	7	3.33
Transferability	1	0	0	2	0	0	0	0	0	0	0	0	0	0		3	1.43

[1] The weighting factor w is calculated by $w_i = \frac{s_i}{\sum_{i=1}^{15} s_i}$ [%]

Based on the "paired-comparison"-method the evaluation criterion "Stability of Position" was defined as the most important and the criterion "VO- & VC Realization" as the least important one.
The determined weighting factors were applied in the "Weighted Objectives"-method to identify in a more objective and replicable way, which concept has the highest potential for further elaboration. Following the "weighted objectives"-method as described in Boeijen's Delft Design Guide [9], the conceptual solutions were ranked regarding to what extent they fulfill the evaluation criteria. For this purpose, points between zero and ten were assigned for each evaluation criteria to the different concepts. Zero points illustrate the concept not satisfying the criterion at all. Ten points symbolize the criterion being fully achieved. The allocated points are then multiplied with the weighting factor of the corresponding criterion so that the weighted points are calculated. When adding up the weighted points of all criteria, the most promising conceptual solution is revealed. The "weighted objectives"-method conducted to evaluate the six concept alternatives is presented in Table 5.

Table 5: "Weighted-Objectives"-method: Points are allocated depending on how well the concept fulfills the particular critrion. The points range from 0 (the concept does not meet the criterion at all) until 10 (the concept totally fulfills the criterion) [9]

		Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5		Alternative 6	
	Weighting [%]	**Points**	**Weighted Points**	**Points**	**Weighted Points**	**Points**	**Weighted Points**	**Points**	**Weighted Points**	**Points**	**Weighted Points**	**Points**	**Weighted Points**
VO- & VC Realization	0.48	1	0.00	1	0.00	1	0.00	1	0.00	2	0.01	1	0.00
Stability of Position	12.38	5	0.62	3	0.37	4	0.50	3	0.37	8	0.99	5	0.62
Physiological Kinematic	4.76	6	0.29	5	0.24	5	0.24	8	0.38	9	0.43	6	0.29
Deviation to Michelangelo Thumb	2.86	8	0.23	8	0.23	8	0.23	8	0.23	8	0.23	8	0.23
Opening Width[1]	8.10	-	-	-	-	-	-	-	-	-	-	-	-
Harness Control	10.48	7	0.73	7	0.73	7	0.73	7	0.73	7	0.73	7	0.73
Altering Force	9.52	7	0.67	5	0.48	3	0.29	9	0.86	5	0.48	7	0.67
Cable Excursion[1]	9.05	-	-	-	-	-	-	-	-	-	-	-	-
Light Weight	6.19	7	0.43	3	0.19	9	0.56	6	0.37	4	0.25	6	0.37
Robustness	11.43	5	0.57	3	0.34	8	0.91	6	0.69	8	0.91	1	0.11
Cable Deviation	7.62	10	0.76	8	0.61	10	0.76	10	0.76	9	0.69	10	0.76
Dimensioning	8.10	6	0.49	3	0.24	3	0.24	7	0.57	6	0.49	5	0.40
Manufacturing Costs	4.29	5	0.21	3	0.13	9	0.39	7	0.30	2	0.09	2	0.09
Complexity	3.33	5	0.17	4	0.13	9	0.30	9	0.30	3	0.10	4	0.13
Transferability	1.43	6	0.09	6	0.09	4	0.06	2	0.03	6	0.09	6	0.09
	Sum		5.26		3.78		5.20		5.59		5.47		4.50

[1] Characteristics of the whole hand rather than the thumb. Hence, it is not rateable at this status of the design.

In the evaluation of the concepts no assessment was conducted regarding the criteria of "Opening Width" and of "Cable Excursion", because they are characteristics of the whole hand rather than the thumb switching mechanism. Therefore, they were not rateable at the current design status.
Alternative 4 achieved with a total number of 5.59 points the highest ranking followed by *Alternative 5* with a total number of 5.47 points. Despite the narrow result, the point allocations distinctly revealed, that *Alternative 4* was expected to have the highest potential; it obtained in almost all assessed evaluation criteria points higher than average. Solely in the criteria of "stability of position", "Transferability" and "VO- & VC-Realization" *Alternative 4* was rated very low. In the latter two criteria, the low scores are insignificant since these criteria represent a wish rather than a requirement for the design. The criterion of "Stability of Position", on the contrary, has been judged with the "paired-comparison"- method (Table 4) to be the most significant characteristic. However, the stability of *Alternative 4* could easily be improved by equipping the thumb dummy with a stationary ball joint. Consequently, *Alternative 4* was chosen to be further elaborated.

6. Concept Elaboration

In this Section 6 and Section 7 the elaboration of the concept *Alternative 4* will described in more detail than conducted in the scientific paper, in which solely the final version of the body-powered co-contraction equivalent is presented. In the actual design process, however, multiple revision cycles had to be carried out before achieving the properly functioning model as described in the following. In this Section 6 the first version of the body-powered co-contraction equivalent is addressed. It is described how each component of the conceptual solution was at first realized with the computer-aided design (CAD) software *PTC Creo Parametric 2.0* in a 3D model. Moreover, the interaction of the components is elucidated and the dimensioning of the parts explained. Lastly, the manufactured model and the difficulties which it caused will be presented. This will lead to the following Section 7, in which the concept revision is thematized.

6.1. Implementation of the Original Concept

Hereafter the way each component was exactly realized in the first version of the body-powered equivalent will be described in more detail. An overview of all components of the conceptual solution and their implementation in 3D is given in Table 6.

Pathway

The final parabolic pathway was curved in three dimensions as shown in Figure 4. It was milled into a solid component, so that a pin can be guided within the two pathway branches. Each branch represented a different grip type: the upper branch equals the lateral grip and the lower one the opposition grip. At the end position of each branch, the hand was fully closed in the respective grip type. The intersection of both branches corresponds to the open-palm grip, which equals the maximally opened hand. Here, a cylinder was milled into the solid component to provide a circular, planar locating surface for the toggle, which was responsible to direct the thumb to the other pathway branch. Parallel to this, an arc was constructed in a more lateral position to serve as a locating surface for the dovetail of the toggle. It also defined the range of motion of the toggle.
Below the toggle's dovetail locating surface material got removed as extension of the toggle's locating surface. In this way a cuboid shaped spring recess was created, in which the toggle spring could act. The other visible cuttings in the solid component were required for additional connecting elements.

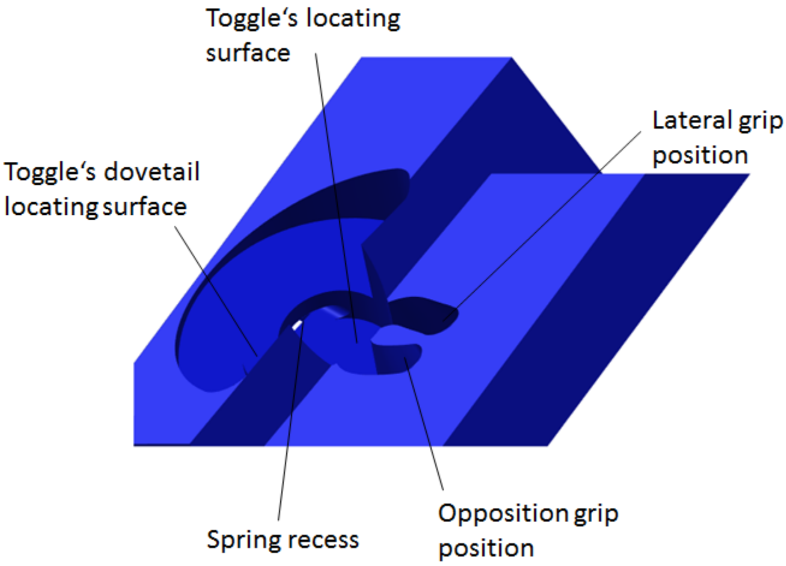


Figure 4: 3D implementation of the pathway component

Thumb

The originally sliding thumb was equipped with a ball joint (Figure 5). The joint was fixed in place, so that any translational movement of the thumb was prevented. Consequently, changes in the grip type were accomplished by means of rotation of the ball joint leading to a tilting movement of the thumb dummy. The actual thumb movement was defined by the thumb guiding pin, which extended the thumb shaft below the ball joint. The thumb guiding pin could only move within the milled pathway as shown in Figure 5. Hereinafter the pathway branch, the thumb pin is currently located in, will be referred to as "active branch". Correspondingly, the opposite pathway will be called "inactive branch".

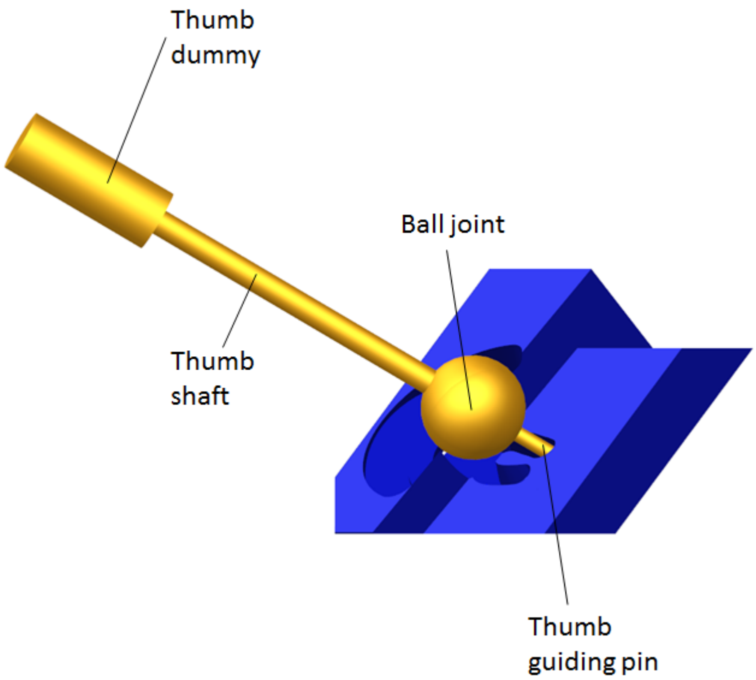


Figure 5: 3D implementation of the thumb dummy and its motion, which is defined by the thumb guiding pin moving along the milled pathway

Due to the stationary ball joint and the pin guided within the pathway, a distinct thumb movement could be accomplished with increased position stability. Moreover, in addition to the change of thumb position, thumb flexion was also realized by the ball joint.

Toggle with spring

The originally cylindrical toggle with two notches was expanded by a dovetail as illustrated in Figure 6 a). Moreover, major parts of its bottom locating surface were removed, so that a tension spring could act on the toggle from below.
The toggle was positioned on the planar circular surface within the circular cutting of the solid pathway component as shown in Figure 6 b) . The tension spring attached at the toggle's bottom could emerge through the spring recess (visual in Figure 4). Its other end was mounted to a wall of the solid pathway component within the spring recess.
In addition to the small locating surface on its bottom the toggle was rigidly supported by its dovetail contacting the dovetail locating surface (visual in Figure 4) parallel to the other locating surface. Hence, tilting movement of the toggle was supposed to be prevented. Furthermore, the dovetail could be used to restrict the toggle's range of motion by establishing specific end positions for its movement. Generally the toggle could rotate within the cuttings in the solid component and therefore, direct the guiding thumb pin from one pathway branch to the other one. To receive the thumb guiding pin, the toggle comprised the two notches, of which each one extended the curvature of one pathway branch. After a change of the grip type, the active pathway and the corresponding notch had to match to enable a consecutive switching procedure. The two positions, in which one of the notches at a time matches its corresponding pathway branch, had to coincide with the two end positions of the toggle as defined by its dovetail.
The tension spring attached below the toggle was responsible for bringing the toggle to an end position and thus, to ensure the system to be ready for a following application.

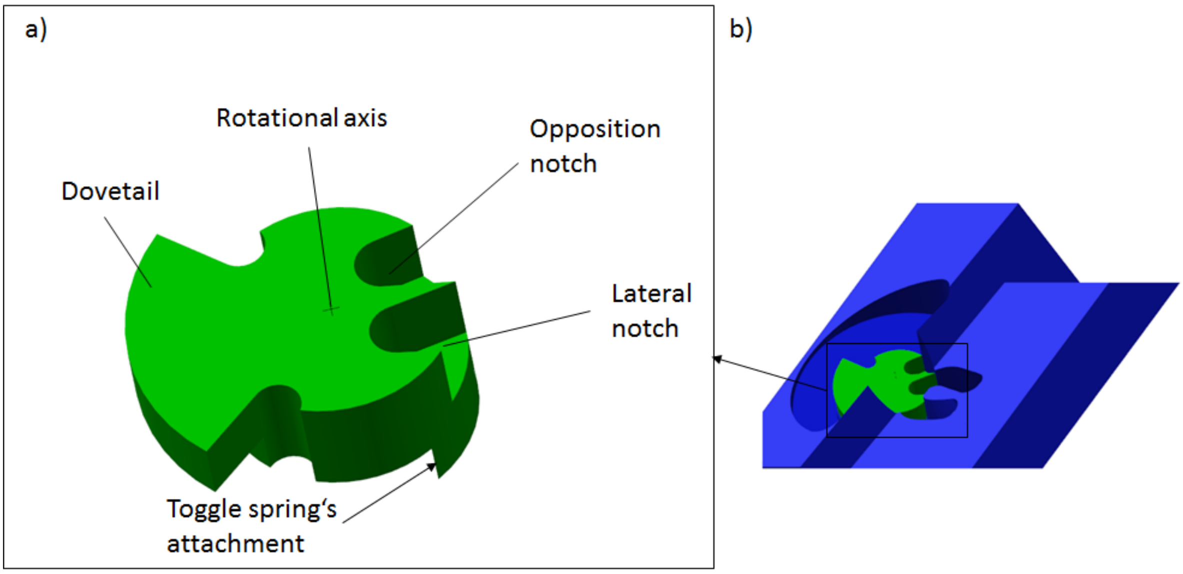


Figure 6: 3D implementation of the toggle component and its position within the pathway component

Retraction spring

In order to achieve a high spring rate and hence, high gripping forces without requiring large diameter springs, two springs were utilized for retraction. Due to the design of their mounting, a spring could be positioned on each side of the thumb axis. In addition to high force values, the symmetrical implementation of the force application points was believed to be favorable for the system to reduce the drift of the thumb.
A mounting plate for the retraction springs was screwed onto the thumb shaft above the ball joint. Hence, the second mounting was positioned on the palm dummy (fig.rückstellfeder). Consequently, the springs always exerted a pulling force on the thumb causing the hand to close as soon as the amputee released the control force.

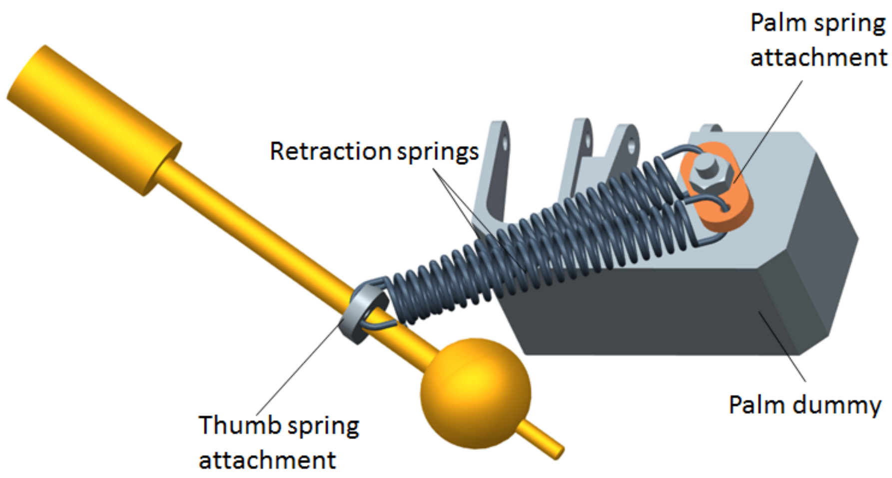


Figure 7: Attachment of the retraction springs in the 3D implementation of the conceptual solution

Force application

Just as common body-powered prostheses, the control force was applied to the device by means of a Perlon cable. When the amputee tensioned this cable, the hand got opened. As soon as the maximum hand opening width was reached, additional control force applied by the user led to a change of the grip type.
The Perlon cable was fixed to the thumb shaft above the ball joint and was orientated in opposite direction to the retraction springs (Figure 8). The distance between the cable fixation and the ball joint's center of rotation influenced the force required by the amputee to move the thumb: the higher the cable is positioned on the thumb shaft, the less force is needed.
So far, the control cable was solely attached to the thumb shaft. Nevertheless, it was intended to combine the thumb control with the mechanic of the other fingers, so that in the long term only one control cable was needed to open the whole hand as well as to change the grip type.

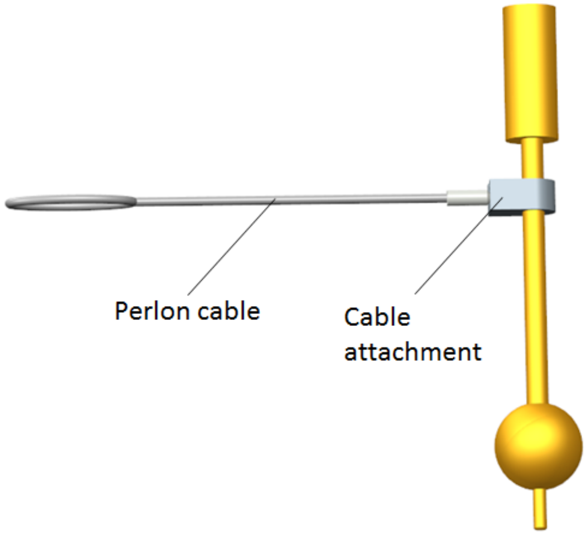


Figure 8: Implementation of the force application in the 3D implementation of the conceptual solution

Additional components such as a stationary bearing for the ball joint or a lid to put over the toggle's dovetail to prevent tilting movements were added to the just described components in order to obtain a functional and manufacturable 3D model of the concept. As required, the components were linked by screw connections. Moreover, the mechanism was fixed to a base plate for rigid support. The index and the middle finger of the Michelangelo Hand were added to the switching device for illustration purposes.

The final 3D CAD model of the first version of the body-powered co-contraction equivalent is illustrated in Figure 9 in its lateral grip (left) and in its opposed grip (right).

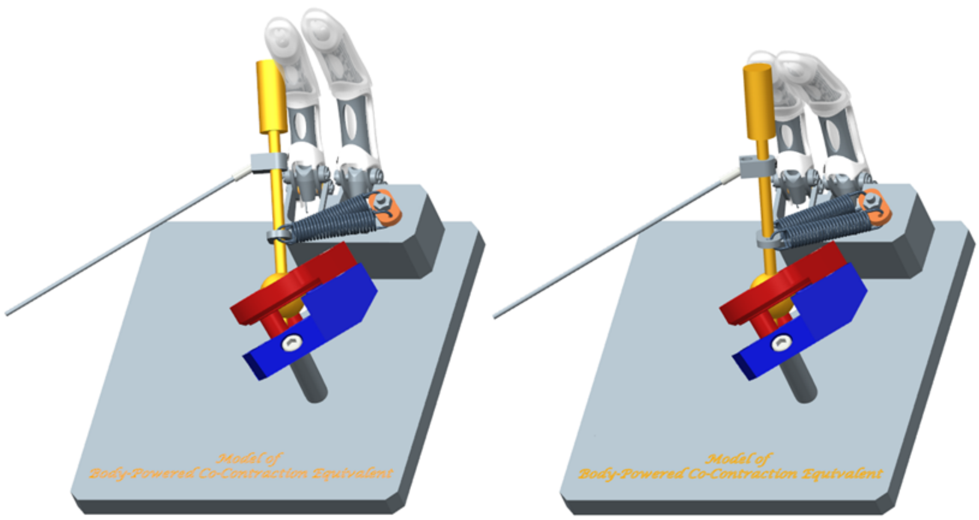
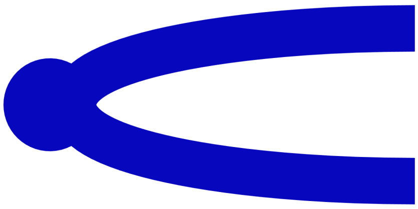
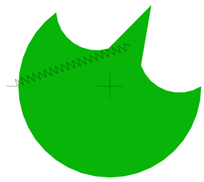
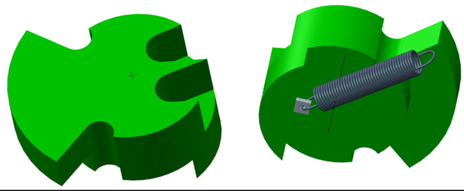
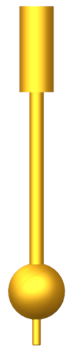
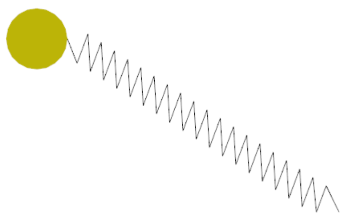
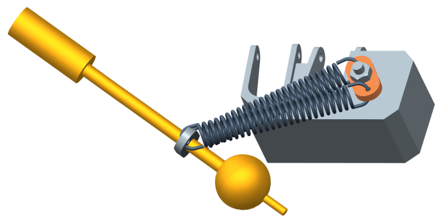
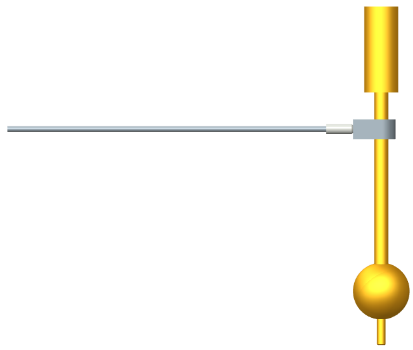


Figure 9: Final 3D CAD model of the original concept

Table 6: Overview of the implementation of the conceptual solution

Component	Conceptual Solution	Elaborated Concept
Pathway		
Toggle with toggle spring		
Thumb		
Retraction spring		
Force application		

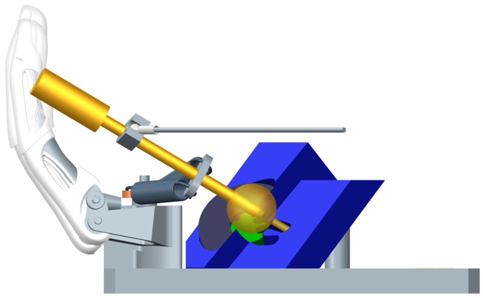
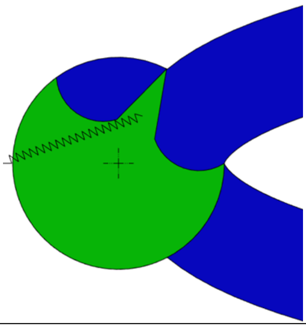
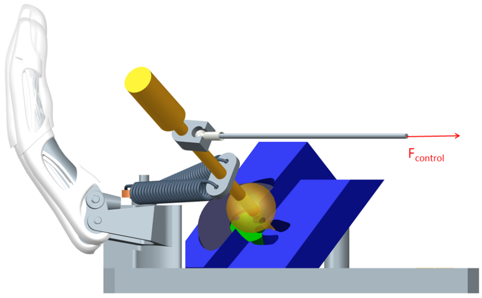
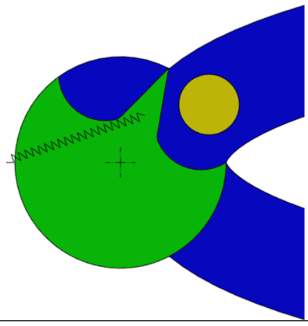
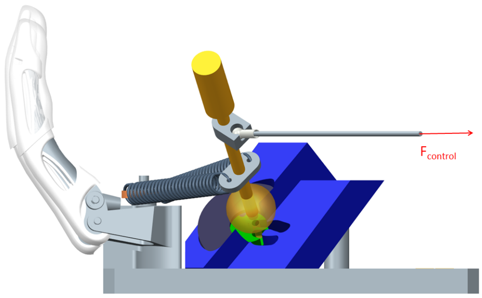
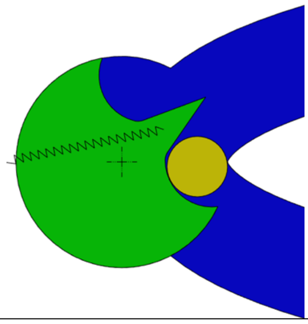
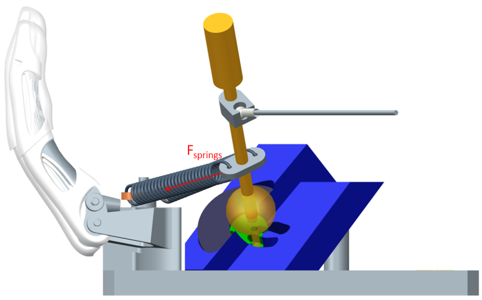
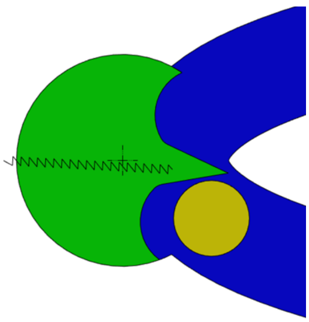
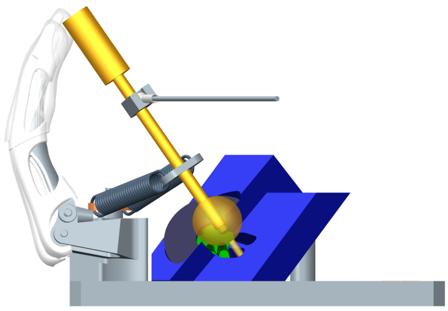
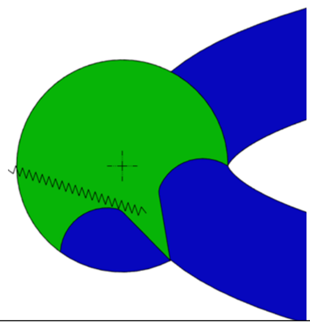
6.2. Mode of Operation of the Original Concept

To elucidate the concrete mode of operation of the mechanism, consequent steps of a switching procedure from the lateral to the opposition grip are illustrated in Table 7 and described in the following. In Table 7 components not directly contributing to the switching (e.g. ball joint bearing) are faded in the final 3D model. For a better understanding, the interaction of toggle and toggle spring is added to Table 7 in the form of a 2D concept.

- **Lateral grip**: To realize the lateral grip, the thumb guiding pin is positioned in its lateral end position of the upper pathway branch. The toggle is rotated to its lateral end position, so that the lateral toggle notch matches the active, lateral pathway branch.
- **Thumb guiding pin entering toggle**: When the amputee tensions the control cable ($F_{control}$), the thumb guiding pin is guided along the lateral pathway branch towards the pathway apex. The thumb tip on the contrary is abducted moving towards its open-palm position. The retraction springs attached to the thumb shaft above the ball joint are tensioned due to this abduction movement. During the thumb's motion towards the open-palm position the thumb guiding pin finally hits the inclined wall of lateral toggle notch and gets directed to the notch's low point.
- **Rotation of toggle**: Additional force applied to the control cable causes the guiding pin to press against the wall of the notch's low point and hence, initiates clockwise rotation of the toggle. When the longitudinal axis of the thumb guiding pin aligns the pathway apex, the maximum opening width of the hand is reached. When it is moved past the pathway apex and thus hyperflexes the thumb, a change of the grip type is initiated.
- **Thumb guiding pin exiting toggle**: When the lateral toggle notch, in which the thumb guiding pin is currently located in, matches the opposition pathway branch, the thumb guiding pin enters this branch in case the control force is release. Then the preloaded retraction springs $F_{springs}$ pull the thumb shaft towards the other fingers. Consequently, the thumb guiding pin gets dragged along the opposition pathway branch towards its opposition end position.
- **Opposition grip**: After the thumb guiding pin exited the lateral toggle notch and in case the tip of the toggle has passed the pathway apex, the toggle spring continues the clockwise rotation of the toggle to the toggle's opposition end position. This way, the mechanism gets prepared for the next switch of the grip type.

Before the manufactured model of the first version of the body-powered co-contraction equivalent is presented, the dimensioning of the components is depicted.

Table 7: Consequent steps (left column) of a switching procedure from the lateral to the opposition grip are shown by means of the 3D model (middle column) and the corresponding interaction between toggle and toggle spring by means of a conceptual drawing in 2D (right column). In the 3D model $F_{control}$ represents the force applied by the amputee to the control cable. $F_{springs}$ illustrates the total force exerted by the springs. The ball joint bearing and other connecting elements are faded in the 3D model.

Description	Model	Conceptual Toggle
Lateral grip		
Thumb guiding pin entering toggle		
Clockwise rotation of toggle		
Thumb guiding pin exiting toggle		
Opposition grip		

6.3. Dimensioning

The aim of this work was to develop a mechanism to vary the grip pattern as a first design step for a body-powered alternative to the Michelangelo Hand. Since the actual properties of the Michelangelo Hand are supposed to be realized in the long term, the thumb positions achieved with the designed mechanism should match the positions of the Michelangelo thumb for the corresponding grip. Since the CAD files of the Michelangelo Hand were available, the dimensioning of the switching mechanism was based on these.

Thumb Positions

First of all, the coordinates of the thumb finger tip during the lateral, the open-palm and the opposition grip were extracted from the CAD files of the Michelangelo Hand. Moreover, the coordinated of the longitudinal axes of the Michelangelo thumb were obtained as well. The Michelangelo thumb comprises two longitudinal angled axes, because its interphalangeal joint (IP) is designed with a constant preflexion.
In addition to the extracted coordinates of the thumb finger tip and the axes the hand chassis was transferred as palm dummy to the new design in order to retain the correct relative positions between the thumb finger tip and the hand palm. Though the hand chassis was adapted and simplified for the switching mechanism. Based on the extracted coordinates of the thumb finger tip in the different grip types and the corresponding position of the hand chassis, the switching mechanism was constructed as illustrated in Figure 10.

Ball Joint Center of Rotation

Physiologically, the rotational movement of the human thumb from the lateral, the open-palm or the opposition position to another one of these extreme positions is named circumduction. In literature the thumb's circumductional movement is approximated as a cone with the cone apex positioned in the carpometacarpal joint (CMC). Though, the thumb's kinematic is physiologically an interaction of the thumb's CMC and its metacarpophalangeal thumb joint (MCP) [10]. For simplicity, the two physiologically interacting thumb joints were realized in the designed mechanism as one ball joint. Its position was determined by means of the cone approximation of the thumb's circumductional movement as illustrated in Figure 10. Here the longitudinal axes of the index and the middle finger were added for a better perception of the hand orientation.

In Figure 10 a) the relative position of the points representing the thumb finger tip during the lateral (green), the open-palm (turquoise) and the opposition grip (orche) to the palm dummy are illustrated. The points were connected, by which the base of the circumduction cone was created (Figure 10 b)). The cone axis (Figure 10 c)) was constructed orthogonal to the cone base through its center point. The apex of the cone and hence, the ball joint center of rotation could be positioned arbitrarily along this cone axis (Figure 10 d)) since the length of the thumb shaft was adapted accordingly. In this way, it was guaranteed that the thumb finger tip of the current design coincided with the coordinates extracted from the Michelangelo Hand.
To define the exact position of the ball joint's center, it first had to be decided if other components such as the pathway, the toggle or the retraction springs were arranged above or below the ball joint.

Arrangement of toggle, pathway and retraction springs

Eventually the switching mechanism should contribute to an anthropomorphic hand design. For this purpose, it was advisable to arrange the components of the switching mechanism such, that they could be hidden within the hand chassis. Depending on the toggle, the pathway and the retraction springs being positioned above or below the ball joint, major parts of these components were either orientated in the direction of the palm dummy or away from it. If the component is orientated towards the palm dummy, it can probably be completely hidden within the chassis on the long term. Hereinafter, all possible combinations of the arrangements of these components were studied to reveal the most suitable one. Since the toggle position implicates the orientation of the pathway, only the location of the toggle was investigated. In Table 8 the possible combinations of toggle and retraction springs positioned above or below the ball joint and the resulting orientation towards or away from the palm dummy are summarized.

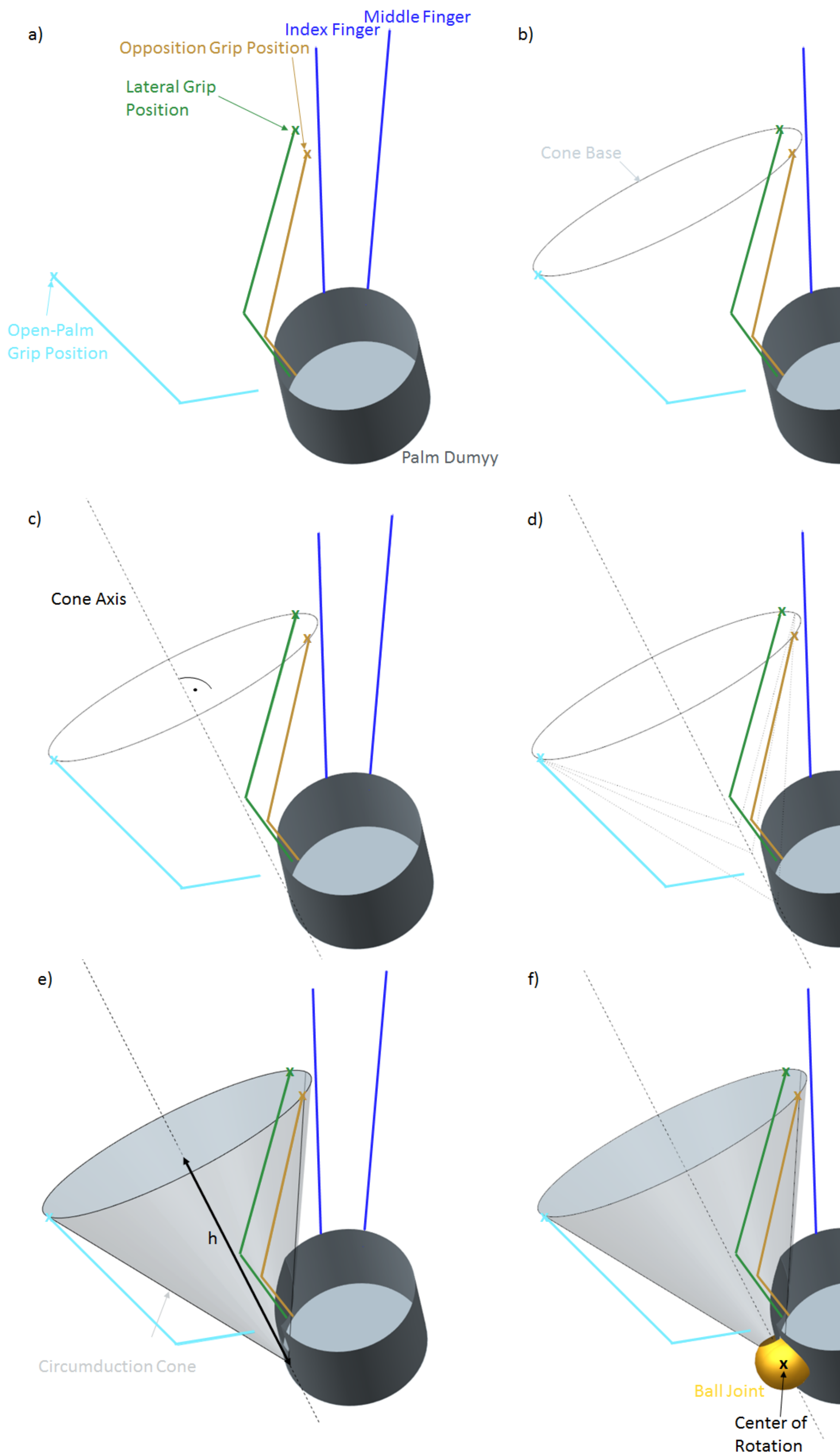


Figure 10: Step-by-step deviation of the position of the ball joint based on the approximation of the thumb's circumduction movement between the lateral, the open-palm and the opposition grip as a cone with the apex in the CMC [10]: a) Thumb finger tips' coordinates and axes of the thumb derived from the Michelangelo Hand; b)-e) Construction of circumduction cone; f) Derived position of the ball joint

Table 8: Possible arrangements of the toggle and the retraction springs resulting in the components to be orientated in the direction (towards) or in the opposite direction (away) of the palm dummy

Position	Springs' orientation	Toggle position
Both components above ball joint	towards	away
Both components below ball joint	away	towards
Springs above & Toggle below ball joint	towards	towards
Toggle above & springs below ball joint	away	away

If the retraction springs are positioned above and the toggle positioned below the ball joint, both components are orientated in the direction of the palm dummy and hence, can be located within the hand chassis.

Based on this a cone height of 86 mm was chosen, so that the cone apex lies approximately in the middle of the palm volume leaving space for the retraction springs above and space for the pathway below the ball joint (Figure 10). The chosen position led to a distance of 100.28 mm between the ball joint's center of rotation and the top surface of the thumb dummy.

Pathway

The exact pathway geometry was generated on the basis of the chosen ball joint position as displayed in Figure 11.

For this, each point of the thumb finger tip in a particular grip type was connected to the ball joint's center of rotation (11 a)). Identical cylinders were aligned along these axes and their volumes were extended passed the ball joint's center of rotation (11 b)), because the pathway was intended to be located below the joint. By means of the lateral cylinder's (green) and the opposition cylinder's (ocher) parts below the ball joint the two end positions of the thumb guiding pin were created. The open-palm cylinder's (turquoise) part below the ball joint represents the intersection of the two pathway branches. The lateral cylinder (green) as well as the opposition (ocher) cylinder were connected to the open-palm cylinder (turquoise) creating a negative image of the pathway (11 c)), which curvature was milled in the solid pathway component. Consequently, the pathway was designed such, that the thumb always moves from its current active grip type towards the open-palm grip. This maximally opened hand position also defines the point of grip type switch. For this reason, the open-palm (turquoise) cylinder was eccentrically enlarged to construct a locating surface for the toggle (11 d)). By means of the offset of the enlargement from the center axis of the open-palm cylinder, it was determined how the pathway branches merge into the toggle's locating surface. This, in turn, had to be well adjusted to the toggle design in order to ensure a continuous functionality of the system.

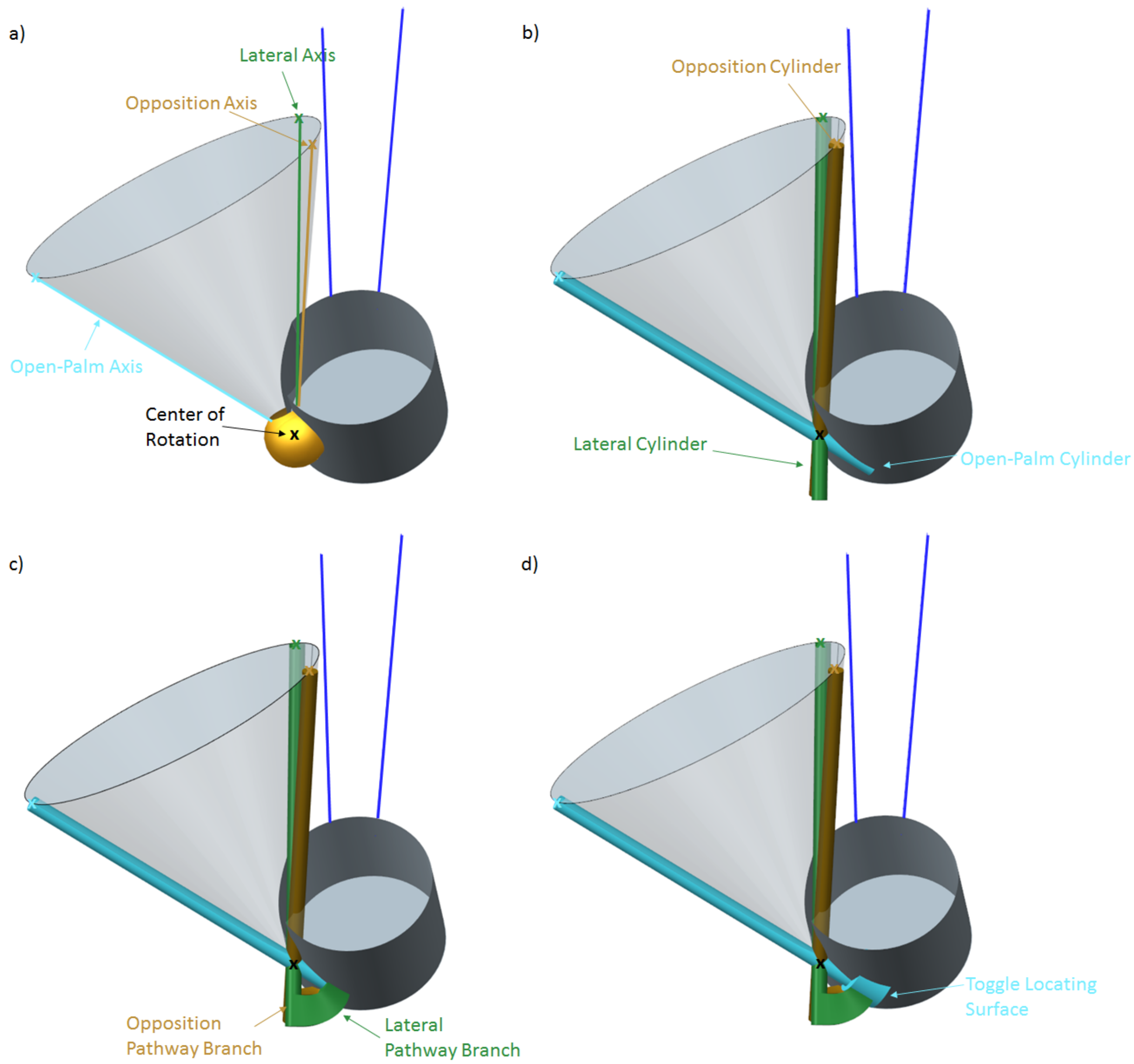


Figure 11: Step-by-step deviation of the exact pathway geometry: a) Axes connecting thumb finger tips' positions to ball joint's center of rotation; b) Implementation of cylinders; c) Construction of the pathway; d) Enlargement of open-palm cylinder to create a locating surface for the toggle

Toggle

The characteristics required for the toggle's geometry to ensure the mechanism to be functional are displayed in Figure 12. Moreover, the forces acting on a toggle notch are indicated.

The control cable of a body-powered prosthesis has a predefined routing, by which the control force acts in a fixed direction. Hence, a component was required, which transfers the thumb pin to the other pathway despite the constant direction of the force application. The toggle was designed to accomplish this task. For this the toggle comprises two notches large enough to embrace the thumb guiding pin. The notches each serve as an extension of one pathway branch. When the toggle matches its corresponding pathway branch, its medial wall coincides with the exterior wall of the pathway.

The medial walls of the toggle notches are inclined such, that the larger force component $F_{\parallel}$ of force $F_{control,1}$, caused by the amputee tensioning the control cable, directs the thumb guiding pin further into the notch. Once the thumb guiding pin has reached the low point of the notch, additional force $F_{control,2}$ applied by the amputee creates with the lever arm l a torque inducing the toggle to rotate. In the configuration drawn in Figure 12 the toggle would turn in clockwise direction.

When the toggle notch, currently comprising the thumb guiding pin, finally matches the other pathway branch, the thumb guiding pin is dragged by the retraction springs after control force release into the newly reached pathway branch. The toggle spring is then responsible to continue the toggle's rotation until it reaches its second end position. In this way the system is prepared for a following switching procedure. For the rotation of the toggle to its other end position, it is mandatory, that the toggle's tip has been moved passed the pathway apex before the thumb guiding pin is able to enter the other pathway branch. Otherwise, the pin will switch the pathway, but the toggle will be dragged by the toggle spring to its initial end position. Consequently, no further grip switch will be possible. This characteristic has to be taken into account, when designing the toggle with its notches as well as the pathway curvature. The occurrence of this will be elucidated in the following paragraph describing the toggle spring.

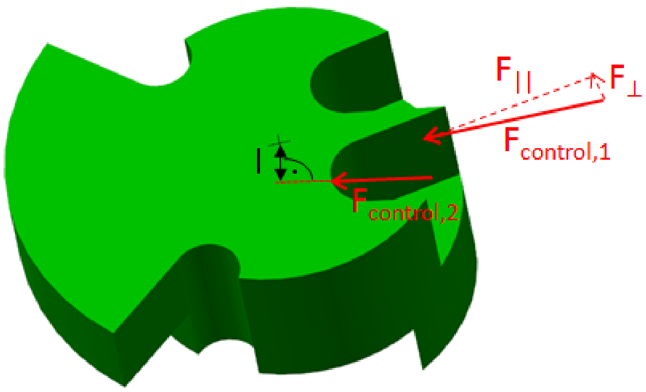


Figure 12: Geometry of the toggle and the forces acting on a notch

Toggle spring

The toggle spring was originally a small tension spring responsible to move the toggle to its rotational end positions.

In order to establish an adequate spring fixation wall below its main surface, the toggle got major parts of his bottom removed. The movable spring end was mounted to the midpoint of this resultant wall. Consequently, this spring end was moved along, when the toggle was rotated. Because of the other spring end being fixed in place, the toggle spring got preloaded in correspondence to the rotation of the toggle.This pretension was the force driving the toggle to an end position once the thumb guiding pin left the toggle.

However, the rotational direction the tension spring facilitates depends on the orientation of the movable spring attachment relative to its dead-center position, where the movable and the fixed spring attachments are displaced by an angle of 180°. In this configuration singularity occurs, because the rotational direction of the toggle is not unique. The spring can only exert an axial pulling force, which is why no rotational movement is proceed. When the movable spring attachment is located on the left of the dead-center position, it drags the toggle to turn in clockwise direction. On the contrary, the toggle is rotated by the toggle spring in counterclockwise direction, if the toggle spring's movable attachment is orientated on the right side of the dead-center position. Consequently, the spring solely continues to move the toggle from its initial end position to the other one, if the movable part of the spring has passed the dead-center position. Otherwise, the spring rotates the toggle back to its initial end position.

The fixed end of the toggle spring is mounted to the solid pathway component. Here the center point of the spring's attachment is located on the midplane between the lateral and the opposition pathway end positions orthogonal to the the toggle's locating surface. Thus, the dead-center position of the toggle spring lies on this midplane. Consequently, it has to be ensured, that the movable spring attachment is always moved over this midplane, before the thumb guiding pin has moved into the other pathway branch.

Retraction Springs

The functionality and the properties of the designed mechanism is highly dependent on the characteristics of the retraction springs. Especially the spring rate R, the pretension $F_{springs,1}$ as well as the distance between the spring force's point of application and the ball joint's center of rotation $l_{springs}$ influence the pinch forces achievable with the mechanism as well as the control forces required to operate the system. Hence, multiple springs in different configurations were planned to be tested with a manufactured model. Based on these tests the most suitable configuration was attempted to be selected for the final model. To choose a variety of springs to be tested, a range of values for the following spring characteristics had to be determined:

- the required spring rate R
- the maximum outer coil diameter D_e
- the length of the unstressed spring l_0
- the maximum spring deflection s_n

The range of values for the following characteristics were defined based on the constructed 3D CAD model:

- the length of unstressed spring $l_0 = [20\,mm;\ 65\,mm]$
- maximum outer coil diameter $D_e \leq 12\,mm$

In the following the spring rate R required for a functional model as well as the maximum spring deflection s_n, which the springs need to be able to achieve, are estimated. For this, the following properties are targeted for the designed mechanism:

- When the hand is fully closed, a pinch force $F_{N,1}$ of at least 8 N should be achieved as comparable to the pinch force c.p. achieved with Otto Bock's Hook *10A71*.
- When the hand is fully opened, a pinch force $F_{N,2}$ of at least 30 N should be achieved.
- The maximum distance o_{max} the thumb finger tip is moved should equal 103 mm, which equals the diameter of the circumduction cone.

Moreover, for the different spring configuration the resultant maximum control cable forces $F_{cable,max}$ required to fully operate the system were considered in the selection of the springs to prevent tremendously high values.

In the following, the equations required to calculate the maximum spring deflection s_n, the spring rate R and the maximum control cable force $F_{cable,max}$ are presented. For simplification, the springs are assumed to stretch horizontally and the pinch forces to act at the thumb finger tip.

Maximum spring deflection s_n

As illustrated in Figure 13 the equation for the maximum deflection is influenced by the maximum distance o_{max} the thumb finger tip is moved, the lengths of the thumb l_{tip} and the distance $l_{springs}$ between the springs' point of application and the ball joint's center of rotation.

With the second intercept theorem, the maximum deflection is calculated as:

$$\frac{s_{max}}{o_{max}} = \frac{l_{springs}}{l_{tip}} \tag{1}$$

$$\Leftrightarrow \quad s_{max} = \frac{l_{springs}}{l_{tip}} * o_{max} \tag{2}$$

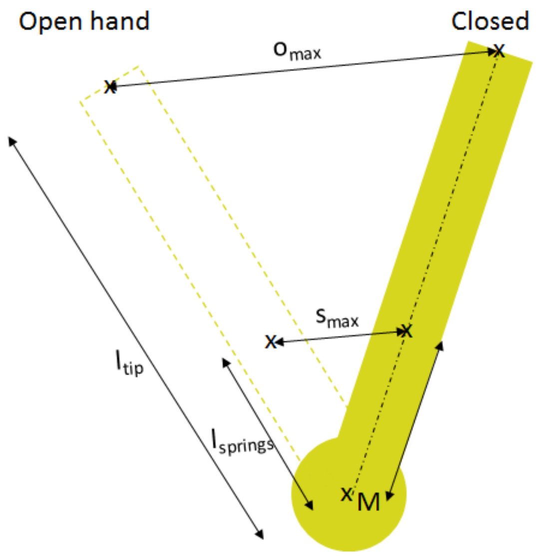


Figure 13: Deviation of the maximum deflection s_{max} of the springs with o_{max} = distance by which the thumb finger tip is moved, l_{tip} = length of the thumb, $l_{springs}$ = distance between the attachment point of the springs and the ball joint's center of rotation

Spring Rate R

The spring rate R is generally defined as the ratio of change in spring force $\Delta F_{springs}$ to the change of spring deflection Δs:

$$R = \frac{\Delta F_{springs}}{\Delta s} \tag{3}$$

Here the change between the pretension of the springs $F_{springs,1}$ and the maximum force exerted by the springs $F_{springs,2}$ is considered.

The equation for the pretension of the springs $F_{springs,1}$ can be derived from the equilibrium state of the forces, which act on the thumb when the hand is fully closed (Figure 14).

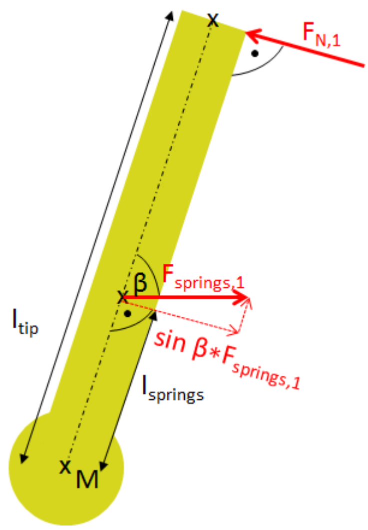


Figure 14: Deviation of the pretension force of the springs $F_{springs,1}$ by considering the equilibrium state of the forces acting on the thumb when the hand is fully closed with $F_{N,1}$ = pinch force, l_{tip} = length o the thumb, $l_{springs}$ = distance between the attachment point of the springs and the ball joint's center of rotation

The pretension force $F_{springs,1}$ of the springs equals:

$$F_{springs,1} * sin\beta * l_{springs} - F_{N,1} * l_{tip} = 0 \quad (4)$$

$$\Leftrightarrow F_{springs,1} = F_{N,1} \frac{l_{tip}}{l_{springs} * sin\beta} \quad (5)$$

The equation for the maximum force exerted by the springs $F_{springs,2}$ can be derived from the equilibrium state of the forces, which act on the thumb when the hand is fully opened (Figure 15).

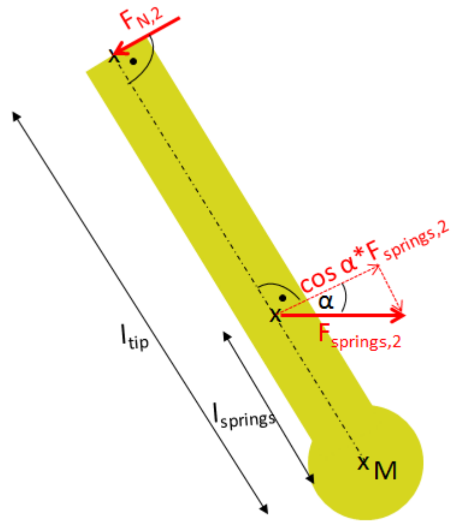


Figure 15: Deviation of the maximum force exerted by the springs $F_{springs,2}$ by considering the equilibrium state of the forces acting on the thumb when hand is fully opened with $F_{N,2}$ = pinch force, l_{tip} = length o the thumb, $l_{springs}$ = distance between the attachment point of the springs and the ball joint's center of rotation

The maximum force of the springs $F_{springs,2}$ equals:

$$F_{springs,2} * cos\alpha * l_{springs} - F_{N,2} * l_{tip} = 0 \quad (6)$$

$$\Leftrightarrow F_{springs,2} = F_{N,2} \frac{l_{tip}}{l_{springs} * cos\alpha} \quad (7)$$

Consequently, the spring rate R can be calculated as:

$$F_{springs,2} - F_{springs,1} = R * s_{max} \quad (8)$$

$$\Leftrightarrow R = \frac{F_{springs,2} - F_{springs,1}}{s_{max}} \quad (9)$$

Maximum control cable force $F_{cable,max}$

The maximum control cable force was estimated, to ensure the chosen spring configuration leading to an acceptable value for the maximum control cable force. As shown in Figure 16 the maximum control cable force $F_{cable,max}$ can be derived as:

$$F_{springs,2} * cos\alpha * l_{springs} - F_{cable,max} * cos\alpha * l_{cable} = 0 \quad (10)$$

$$\Leftrightarrow F_{cable,max} = F_{springs,2} \frac{l_{springs}}{l_{cable}} \quad (11)$$

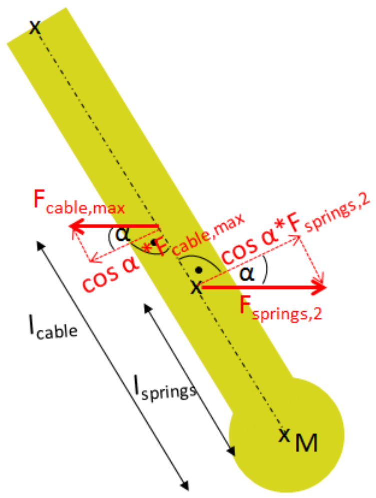


Figure 16: Deviation of maximum force required to control the device $F_{cable,max}$ by considering the equilibrium state of the forces acting on the thumb when hand is fully opened with $F_{springs,2}$ = spring force, $l_{springs}$ = distance between the attachment point of the springs and the ball joint's center of rotation, l_{cable} = distance between the attachment point of control and the ball joint's center of rotation

The distance between the cable's attachment point and the ball joint's center of rotation l_{cable} was defined as 50 mm.

All remaining magnitudes required to calculated the maximum deflection s_n, the spring rate R and the maximum control cable force $F_{cable,max}$ could be extracted either from the CAD file of the constructed mechanism or from the one of the Michelangelo Hand:

- the thumb length $l_{tip} = 102.3$
- the angle $\alpha = 40°$
- the angle $\beta = 60°$

In order to consider multiple positions of the spring's attachment on the thumb, the distance between the spring force's point of application and the ball joint's center of rotation was defined as $l_{springs} = \{15;\ 20;\ 25;\ 30\}$.

With these magnitudes the Equations 2, 5, 7 and 9 could by solved, by which the ranges of values for the spring's properties were defined as:

- when it is unstressed, a length of $l_0 = [20\,mm;\ 65\,mm]$
- a maximum outer coil diameter of $D_e \leq 12\,mm$
- a spring rate of $R \geq 2\ \frac{N}{mm}$
- a maximum spring deflection of $s_{max} \geq 25\,mm$

Multiple springs, which have characteristics within these ranges, were selected to be tested.
Because of most of the springs' properties being adaptable, the final 3D CAD model was designed very variable as well, so that different springs could be tested with regard to e.g. its position, orientation, pretension and finally, the most suitable spring selected.

Most of the remaining components of the mechanisms (e.g. the bearing of ball joint or the lit for the toggle) were adapted to the ball joint and the pathway geometry with a view to occupy as little installation space as possible.

6.4. Manufactured Model of the Initial Concept

A first model was manufactured by the Otto Bock's *Prototype Development Center*. It is illustrated in Figure 17 in its lateral grip (left) and the opposition grip (right).

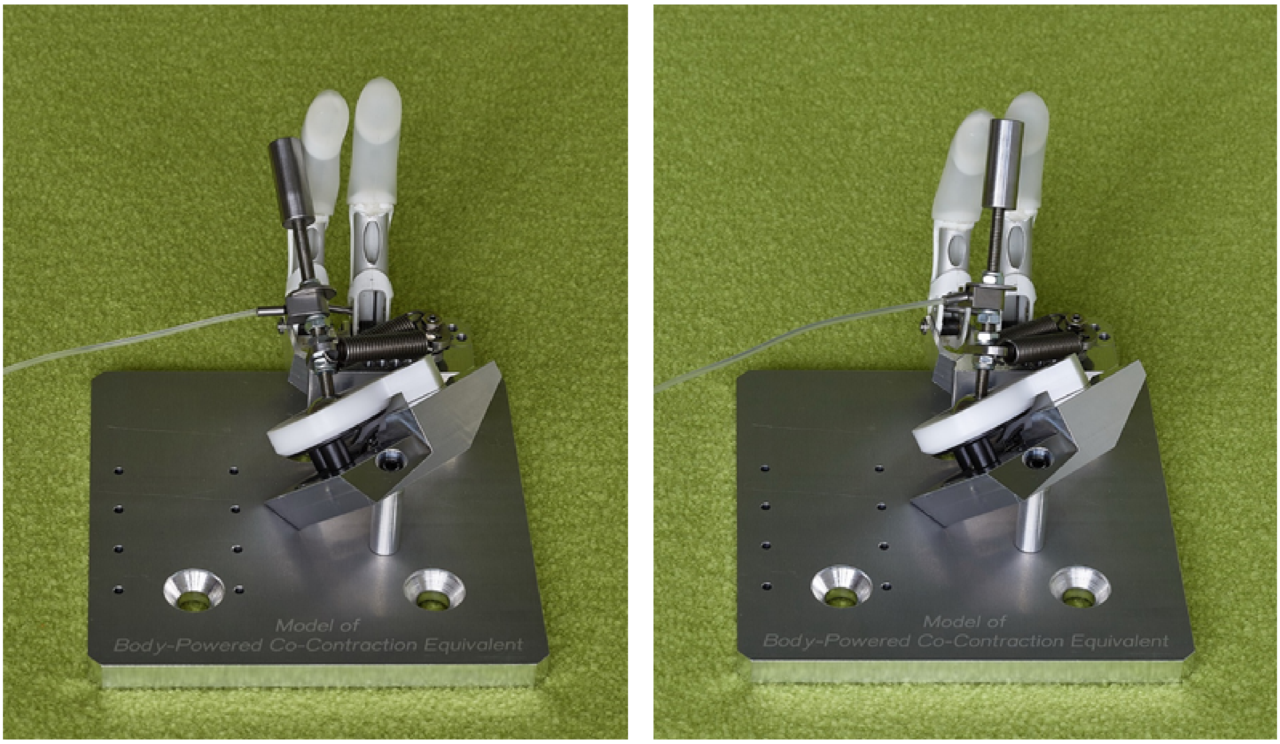


Figure 17: Manufactured model based on the original concept in the lateral grip (left) and the opposition grip (right)

After small adaptations to the contacting surfaces of interacting components it was possible to move the thumb guiding pin from one pathway to the other one and hence, change between the lateral (Figure 17 left) and the opposition grip (Figure 17 right). Unfortunately, the springs, which had been selected to be tested as the toggle spring, had not arrived yet. Consequently, the toggle remained at the position it had reached once the control force was released instead of being moved to one of its end positions.
Provided that the toggle notch, in which the guiding pin was located, matched a pathway branch during force release, the pin was moved by the retraction springs to the end position of the corresponding pathway branch. Despite the notch not corresponding to the active pathway branch remained in contact with the active pathway the grip type could be switched an other time. However, this was solely possible, because the routing of the thumb's control cable could be changed arbitrarily. In reality the amputee can only exert force in a constant direction, which is why the model could not yet been judged as functional.
In order to test the complete functionality of the device despite missing the toggle spring, a titanium wire was fixed to the toggle's spring mounting as shown in Figure 18. By pulling on this titanium wire ($F_{tension}$) the action of the toggle spring was intended to be simulated.

Unfortunately, it was not possible to rotate the toggle by means of the titanium cable to the desired end positions. Only if the toggle was solely slightly shifted from one end position, it could be moved to the adjacen final position by applying several pulling impulses to the titanium wire. By doing so, noises were perceived, which gave the impression of the toggle tilting during its rotational movement. The presumed tilting movements were believed to result from the toggle lacking a distinct rotational shaft. In order to prevent possibly existing tilting movements adaptations were conducted to the first manufactured model. First of all a shaft was forced in the toggle's center to establish the desired rotational shaft. Additionally, the design of the lit, which had been positioned over the toggle's dovetail to pre-

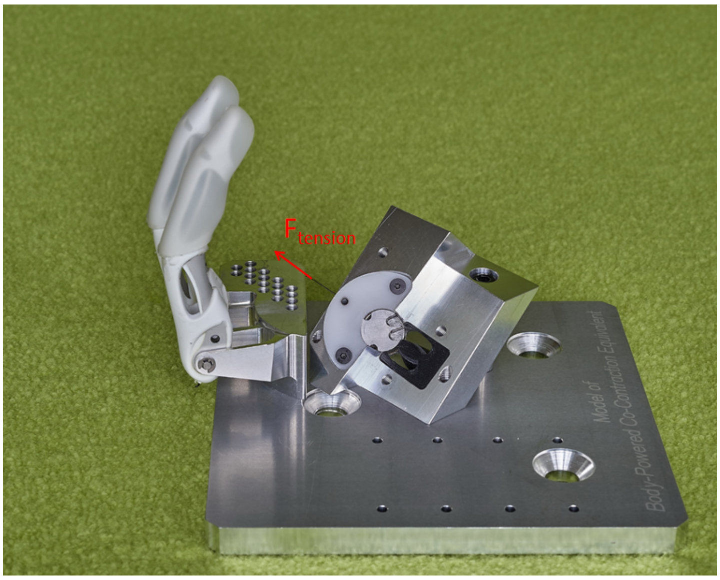


Figure 18: Functional testing of manufactured model by simulating the action of the toggle spring by means of a titanium wire; the thumb with its ball joint and the corresponding bearings were demounted for illustration purposes

vent it from detaching from its locating surface, was revised. As can be seen in Figure 19 the lit got enlarged. By this, a bearing for the rotational shaft of the toggle could be established.

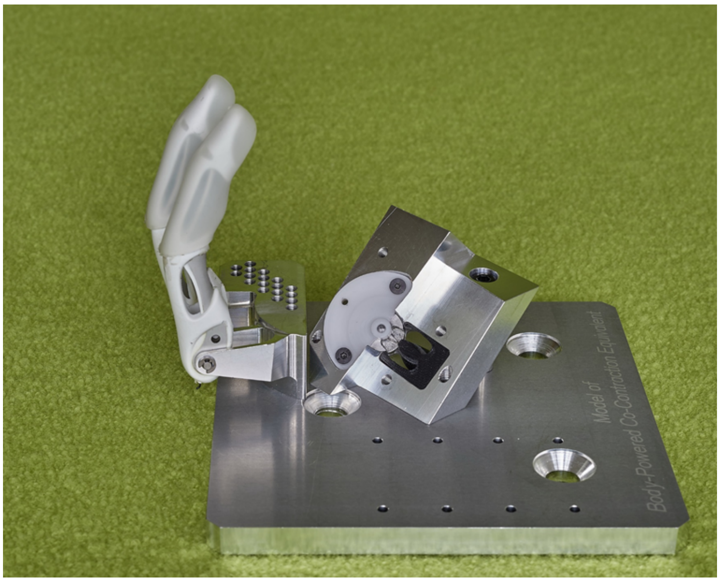


Figure 19: Adaptations conducted to the first manufactured model

Despite the implemented changes, the toggle functionality could hardly be improved. In conclusion, when simulating the toggle tension spring behavior by means of an titanium wire, not enough force could be manually applied to rotate the toggle into either end positions. Since the force, which could manually be exerted on the cable, surpasses force of the potential spring by far, the failure of the ordered springs could be predicted.
Potential causes of the failure of the principle, in which a tension spring is responsible to rotate the toggle to its end positions are marked in Figure 20.

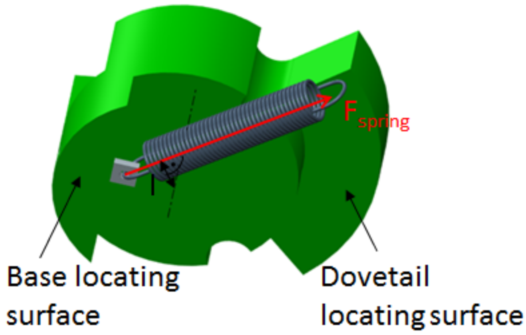


Figure 20: Potential causes of the failure of the current principle, in which a tension spring is responsible to rotate the toggle to its end positions

First of all, the lever arm l of the tension spring force F_{spring} was believed to be too small. Consequently, the torque, the tension spring created, was not large enough to overcome the existing friction. Major parts of the original circular bottom of the toggle had to be removed, so that the toggle spring could be mounted to the resultant wall and act on the toggles from its bottom. However, the material removal reduced the surface area of the toggle's bottom so much, that it was insufficient to serve as a stable locating surface. To improve its safety against tilting the toggle was equipped with a dovetail, which offered a second locating surface to glide on as illustrated in Figure 20. Even though the dovetail was attempted to improve the functionality of the mechanism, it is in the end a potential reason for its failure due to the resulting double guiding. In case of the two different locating surfaces not being perfectly aligned, the two guiding surfaces might counteract each other and hence, block the rotational movement.
Lastly, it can be observed in Figure 21, that the toggle tip has just passed over the system's dead-center position once the pin can move from the notch into the newly reached pathway branch. This is a suboptimal configuration since it bears the risk of the toggle stopping in the dead-center position.
Consequently, the elaborated mechanism had to be revised regarding these properties aiming for obtaining a correct functional model.

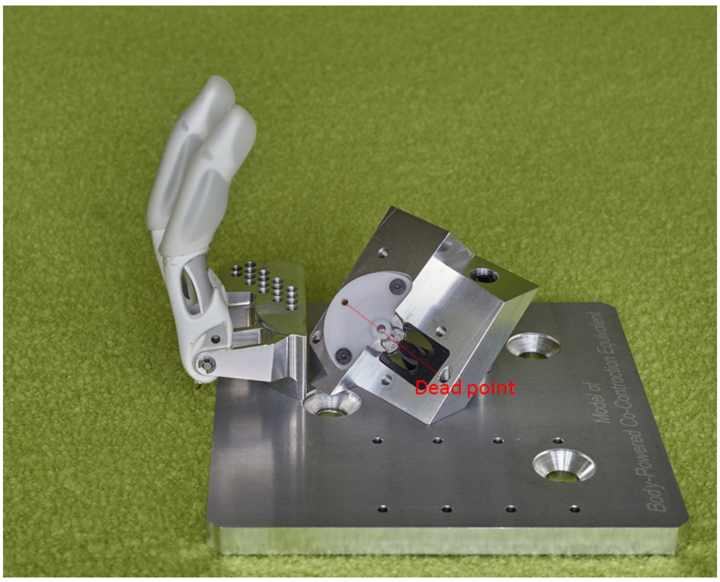


Figure 21: Suboptimal configuration of thumb tip with respect to the dead-center position, when the thumb guiding pin can enter the other pathway branch.

7. Concept Revision

The small lever arm of the spring force as well as the double guiding of the toggle were considered to be the major causes for the failure of rotating the toggle to one of its end positions. Both properties could be corrected by replacing the toggle tension spring with a compression spring functioning from the back of the toggle. Because of the compression spring positioned behind rather than below the toggle, no material had to be removed from the toggle's bottom side. Hence, the toggle kept its bottom side as a planar locating surface. Furthermore, due to the new position of the toggle spring, the lever arm of the spring force was increased. Lastly, compression springs enable higher spring forces while requiring less installation space compared to tension springs.
How the toggle end rotation could be realized by means of a compression spring will be explained in the following. First the revised principle will be illustrated by means of the conceptual solution in 2D. Subsequently, the realization of the new concept in the 3D CAD model will be presented. Based on the changed 3D CAD files a second model was manufactured.

7.1. Conceptual Solution of the Revised Concept

The new concept is based on a compression spring surrounding the shaft of a round head gib. The head of the gib in turn contacts the parabolic shaped tail of the toggle and hence gets affected by its curvature. The functional principle of the concept is illustrated in Figure 22 by presenting a switch from the lateral to the opposition grip step-by-step.

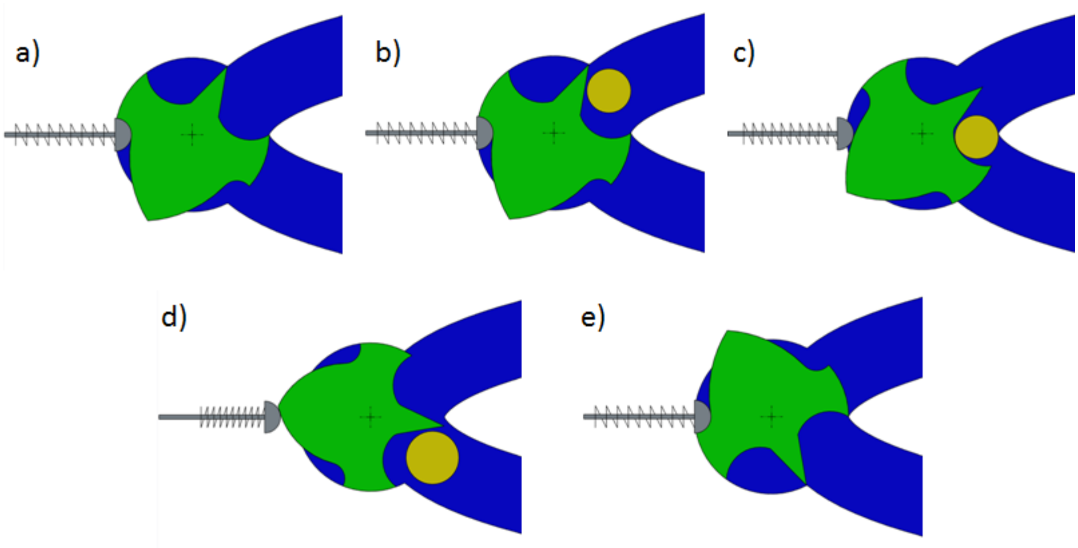


Figure 22: Conceptual solution of the revised concept: the rotation of the toggle to one of its end positions is conducted by the the interaction of a compression spring, a round head gip and the parabolic curvature of the toggle's tail; Interaction of the toggle and the toggle spring during consecutives of a switching procedure from the lateral to the opposed grip: a) Lateral grip; b) Thumb guiding pin entering toggle; c) Clockwise rotation of the toggle d) Thumb guiding pin exiting toggle; e) Opposition grip

In the lateral grip (Figure 22 a)), the thumb guiding pin is located in the end position of the lateral pathway branch. The toggle is turned to its lateral end position, so that the medial, inclined wall of the lateral notch matches the exterior wall of the lateral pathway branch. The compression spring is extended pushing the gib into the recess of the toggle's tail. This way it is ensured, that the toggle stays in its lateral end position.
When the amputee tensions the control cable, the thumb guiding pin is moved along the lateral pathway branch towards the pathway's apex. Hereby the hand approaches the open-palm grip. Shortly before the hand is fully opened, the thumb guiding pin reaches the toggle. Due to the inclination of the notch's medial wall the thumb guiding pin is directed to the low point of the notch (Figure 22 b)). When the control force is continued to be applied, the thumb guiding pin presses against the wall of the notch causing the toggle to rotate clockwise (Figure 22 c)). Hereby, the curvature of the toggle's tail initially pushes the gib in distal direction and so compressing the toggle spring. As soon

as the head of the gib passes over the maximum protrusion of the toggle's tail (Figure 22 d)), the compression spring can expand. Thus, it supports the clockwise movement of the toggle towards its other end position. When the toggle tip has passed its dead-center position, the compression spring and the gip continue to push the toggle to its other end position even after the thumb pin has left the toggle's notch Figure 22 e).

7.2. Implementation of the Revised Concept

In the following the realization of the 2D concept in the final 3D CAD model will be depicted. The revised mechanism, responsible to ensure the toggle reaching one of its end positions is presented in Figure 23.

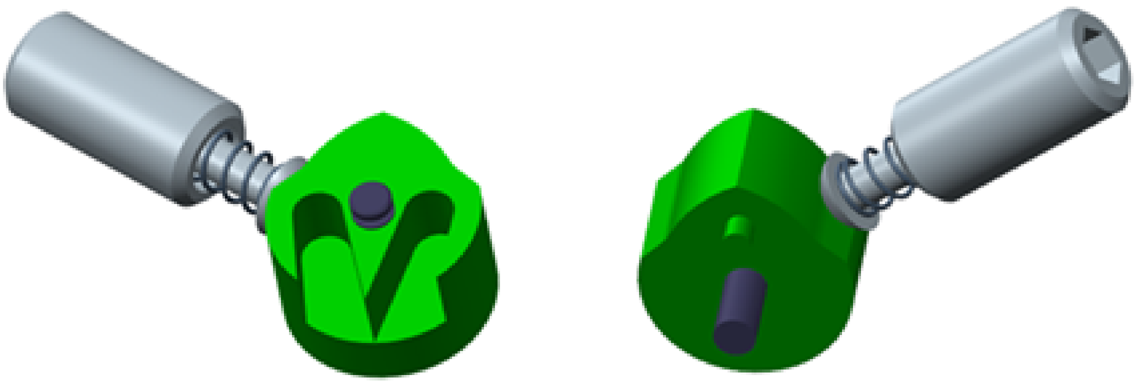


Figure 23: 3D implementation of the revised toggle concept

The earlier conducted adjustment of implementing a defined rotation axis (described in Section 6.4) was carried over to the current toggle design. For this an axis was forced into the center of the toggle's locating surface within the solid pathway component. Correspondingly, a bore was drilled in the center of the toggle, so that it could be slid over this rotational axis.
This time the bottom surface of the toggle was untouched, so that it can serve as a stable locating surface. The original dovetail curvature of the toggle's back got changed to a parabolic shaped tail. The parabolic toggle tail is a major characteristic required to move the toggle to one of its end positions after grip type variation. These end positions are defined by a guiding pin, which is fixed to the bottom of the toggle. The guiding pin moves within a corresponding slot in the solid pathway component. Owing to the boundaries of the slot, the movement of the guiding pin is restricted and hence, the end positions of the toggle are defined.
Apart from the curvature of the toggle's tail, the system responsible to move the toggle to one of its end position consists of a round head gib, a compression spring and a setscrew. A bore got drilled into the setscrew, in which the compression spring was inserted. Within its interior the spring carries the shaft of the round head gib. Consequently, the spring is restricted on the posterior side by the setscrew and on the anterior side by the backside of the gib's head. The shaft of the gib on the contrary can proceed past the spring's stop due to a small through-hole within the setscrew. The head of the gib contacts the parabolic shaped tail of the toggle, so that it gets affected by the tail's curvature. When the toggle is rotated by means of the thumb guiding pin pressing against a notch wall, the tail's curvature initially pushes the gib in distal direction. By doing so, the gib compresses the adjacent spring. As soon as the head of the gib has passed over the maximum protrusion of the toggle's tail, the compression spring can expand and hence, it supports the rotational movement of the toggle towards its other end position.
Due to the spring being positioned within a setscrew, the preloading of the compression spring can be adapted by varying the penetration depth of the setscrew within the toggle lid.

In addition to the system responsible to move the toggle to its end position, the geometry of the toggle notches as well as the curvature of the pathway were adapted.

The geometry of the notches got adapted, so that the low points of the notches lie posterior to the toggle's sagittal plane and in a more lateral position than before. Consequently, the thumb guiding pin is moved further into the toggle component before a toggle rotation is initiated. In this way, the lever arm of the force exerted by the thumb guiding pin on the notch wall was increased. By moving the low points of the notches to a more lateral position it was attempted to ensure the toggle tip having passed the dead-center position before the thumb guiding pin can exit into the newly reached pathway branch.
For the same reason, the radius of the pathway curvature got decreased. In this way, the pathway branches reach the toggle's locating surface in an wider angle. Consequently, the toggle has to be rotated about an larger angle until one of its notches reaches the other pathway branch.

The adaptations to the toggle's tail, the geometry of the notches and the pathway are visual in Figure 24, in which parts of the first version of the body-powered co-contraction equivalent (left) and parts of the second version (right) are presented.

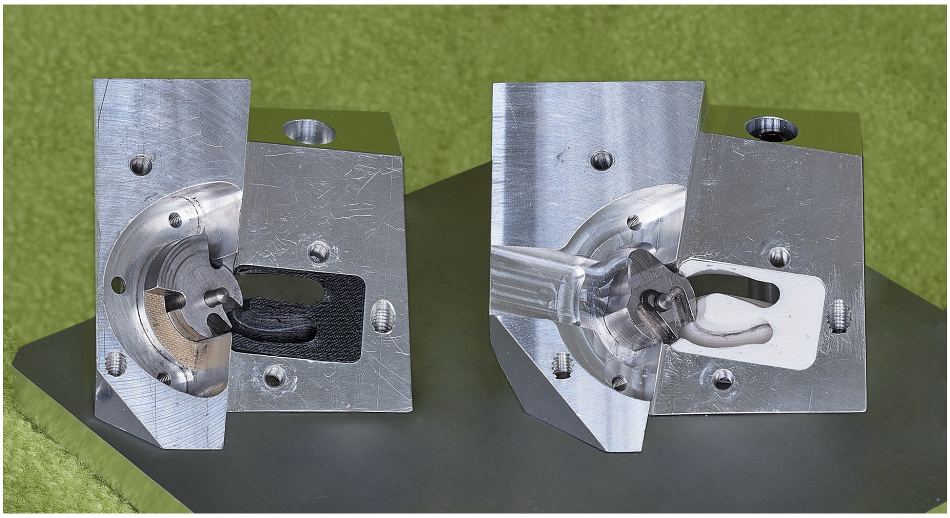


Figure 24: Comparison of the characteristics of the first model (left) and the second model (right)

7.3. Manufactured Model of the Revised Concept

In order to test the revised concept, the solid pathway component, the toggle and a toggle's lid had to be newly manufactured by *Otto Bock*'s *Prototype Development Center*. All other components required for the mechanism could be used from the first manufactured model. The assembled second model is shown in its lateral as well as in its opposition grip in Figure 25.

7.3.1. Mode of Operation of the Manufactured Model

The model represents the mechanism applicable for a left-handed prosthesis. It is a VO-device, so that force applied to the control cable causes the thumb to abduct and to be rotated towards its open-palm position, which represents the maximally opened hand. As long as the control cable force is released before the hand is maximally opened, the thumb is pulled back by the retraction springs to its original grip. Yet continuing to apply a force to the control cable despite having reached the maximum hand opening width initiates the switch of the grip type. Such a grip type switch could already be simulated with the first manufactured model. However, in the first model the toggle was not continued to be rotated to its required end position once the thumb guiding pin had left the toggle's notch. Hence, it was not possible to conduct a consecutive switching procedure. This led to the revision of the concept.
In the second model, on the contrary, the toggle was always moved to one of its end positions once the thumb guiding pin had left into a pathway branch. Thus, consecutive switches of the grip type could be conducted, wherefore the functionality of the revised mechanism could generally be demonstrated in practice.
However, with the manufactured model it has occurred a few times, that the toggle was moved back

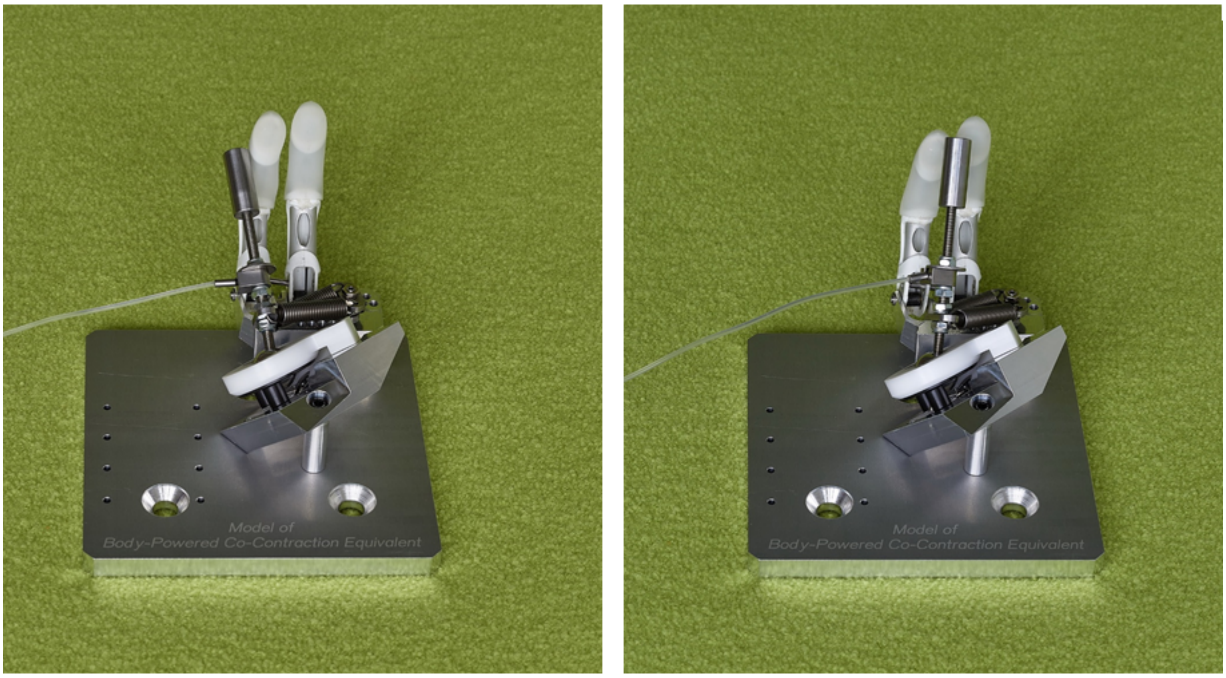


Figure 25: Manufactured model of the revised concept in the lateral grip (left) and the opposition grip (right)

to its initial end position after the thumb had switched the pathway branch. Consequently, one of the toggle notches mistakenly matched the inactive pathway branch rather than the active one. Consequently, it was not possible to change the grip time an other time, because the guiding pin hit against a toggle wall instead of being able to enter a toggle notch. In this case the toggle had to be manually moved to the correct end position.

The occurrence of this implies, that the toggle's tip had not passed the system's dead-center position before the thumb guiding pin exited the toggle's notch even though this characteristic has been taken into account when dimensioning the geometry of the pathway and the toggle. This time, though, the malfunctioning of the mechanism is caused by a reduction in the diameter of the guiding pin, which had in the end been conducted to prevent the pin from jamming inside the notch. As a result, the thumb guiding pin was in fact too small sized compared to the design of the toggle and its notches. Therefore, it was possible for the guiding pin to slip out of the notch way before it was intended to. This reduction of the guiding pin's diameter has to be eliminated in future prototypes.

In consequence of the size deviation between thumb guiding pin and toggle notches, it is recommended for the existing model to continue the force application until no further thumb movement can be observed. This way, the toggle is pushed actively to its other end position. Hence it is ensured, that the toggle's tip has passed the dead-center position before the thumb guiding pin can switch into the other pathway branch. When the controlling force is then released, the thumb guiding pin, driven by the retraction springs, pushes against the medial notch wall causing it to rotate backwards. As soon as the active notch and the nearer pathway branch create a common space sufficient enough for the thumb guiding pin to slide through, it exits the notch into the currently reached pathway branch. Subsequently, the compression spring acts on the toggle and turns it this time into the correct end position.

Keeping this recommendation in mind, the manufactured model can be regarded as a successful demonstration of the functionality of the designed mechanism.

7.3.2. Selection of Model Properties

The model was produced in a very adjustable way, in order to be able to test different spring configurations. For example the mounting plate of the retraction springs was screwed to the thumb's shaft, so that the lever arm and the angle of the spring forces could be varied. Several bores were drilled in the palm dummy in order to be able to also change the position of the other attachment of the retraction springs. This was conducted both to be able to try different springs and to vary their pretension. Likewise, the toggle compression spring had been incorporated in a setscrew. Hence, the preloading of the toggle spring can be changed by varying the setscrew penetration depth. In addition to the springs' characteristics, the point of application of the control force was also realized variably in the model, as the mounting plate of the cable can be moved along the thumb shaft [2].

After having tested different spring configurations, the tension spring *Z-111I* (1.25 X 9.2 X 43.3; EN 10270-1; R= 2.02 N/mm), manufactured by *Gutekunst + Co.KG*, was utilized as the two retraction springs. One mounting of the retraction springs was fixed on the thumb shaft at a distance of around 25 mm to the ball joint's center of rotation. The other attachment of the retraction springs were positioned on the palm dummy in such a way, that the installtion length l_1 of the springs measures 46.6 mm in the lateral and 48.6 mm in the opposition grip. *Gutekunst + Co.KG*'s compression spring *D-049* (0.4 X 4.4 X 11.2; EM 10270-1; R = 0.471 N/mm) was implemented with a preload force of 0.989 N in the model to operate as the toggle spring. The control cable was mounted to the thumb shaft in a distance of around 42.9 mm from the ball joint's center of rotation.
With the selected configuration, properties of the designed mechanism could mathematically be estimated.

8. Model Evaluation

8.1. Estimation of Model Properties

The conducted mathematical calculations to estimate the maximum opening width, the maximum cable force, the maximum cable excursion or the pinch forces at an opening width of 10 mm, 20 mm or 30 mm for the model will be presented in the following. Moreover, the mass of the model was measured.

Maximum opening width

The operation of the control cable, first causes the hand to approach its open-palm grip, which characterizes the maximum opening width of the hand. In this position the tip of the thumb and the one of the index finger span a distance of approximately 117.5 mm. To reach the maximally opened hand configuration, the thumb finger tip has to be moved by 102.3 mm from its lateral grip position and by 97.8 mm from its opposition grip position as illustrated in Figure 26.

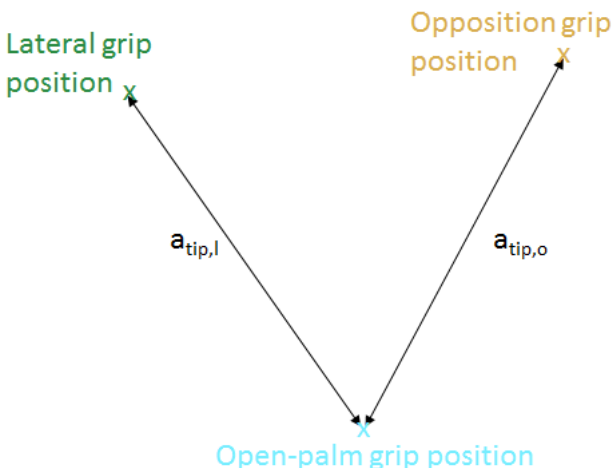


Figure 26: Approximated distance between the positions of the thumb finger tip in different grip types

[2]The large diameter bores in the base plate, which can be seen in Figure 25, serve as attachment points for suctions knobs, by which the base plate can be fixed to the table. The remaining spare bores are backups to enable to test compression springs as retraction springs.

Maximum cable excursion

Based on the deviation in the distance the thumb tip has to cover from its lateral and its opposition grip position to the open-palm one, different amounts of cable excursions are required to open the hand. The cable excursion can be estimated by considering the displacement, the cable attachment point travels from a closed grip to the open-palm grip as visualized in Figure 27.

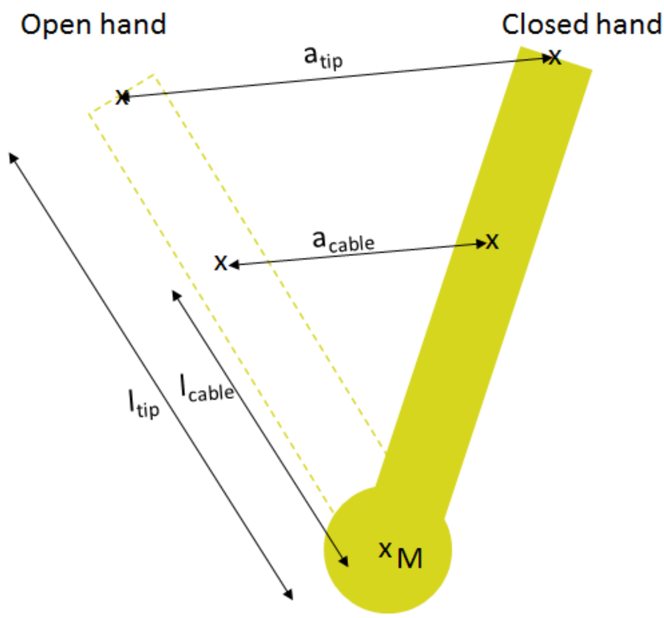


Figure 27: Estimation of the cable excursion by means of the displacement of the cable's attachment point a_{cable} with a_{tip}=distance the thumb finger tip is moved from a closed grip to the open-palm grip, l_{tip} = length of the thumb, l_{cable} = distance between the cable attachment point and the ball joint's center of rotation

Knowing the displacement a_{tip} of the thumb finger tip from a closed grip to the open-palm grip, the length of the finger l_{tip} and the distance l_{cable} of the cable attachment point to the ball joint's center of rotation M, the displacement a_{cable} of the cable attachment point can be calculated by means of the second intercept theorem:

$$\frac{a_{cable}}{a_{tip}} = \frac{l_{cable}}{l_{tip}} \tag{12}$$

$$\Leftrightarrow a_{cable} = \frac{l_{cable}}{l_{tip}} * a_{tip} \tag{13}$$

With $l_{tip} = 100\,mm$, $l_{cable} = 42.9\,mm$, $a_{tip,l} = 102.3\,mm$ and $a_{tip,o} = 97.8\,mm$, respectively the displacement of the cable attachment point and hence, the cable excursion required to fully open the hand equals:

$$a_{cable} \approx \begin{cases} 43.7\,mm & \text{when starting from the lateral grip} \\ 41.9\,mm & \text{when starting from the opposition grip} \end{cases}$$

Consequently, a cable excursion of 43.7 mm is required to fully open the hand starting from the lateral grip. To achieve the open-palm grip from the opposition grip solely an cable excursion of 41.9 mm is needed. The cable excursion is predefined by means of the Michelangelo Hand's thumb positions. Hence the difference cannot be corrected as long as exactly the same thumb positions during the lateral, the opposition and the open-palm grip as with the Michelangelo Hand should be achieved.
Since in both grip types a maximum excursion of less than 53 mm is required to operate the switching mechanism, below-elbow amputees should be capable to operate the device based on this model characteristic.

Maximum Cable Force

Moreover, to guarantee below-elbow amputees to be able to use the device, the maximum control cable force required, cannot exceeds 140 N.
In order to be able to estimate the maximum cable force F_{max} required to operate the system, first of all a general equation for the control cable force F_{cable} is derived by considering a closed hand. As illustrated in Figure 28 the control cable force, applied by the amputee, is counteracted by the spring force $F_{springs}$.

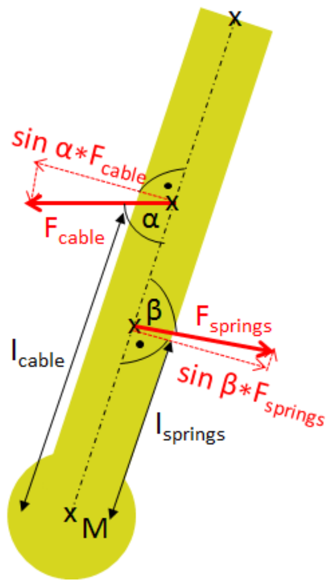


Figure 28: Deviation of the maximum cable force F_{cable} by considering the equilibrium state of the forces acting on the thumb when the amputee operates the cable to open a fully closed hand with $F_{springs}$ = spring force; l_{cable} = distance between cable attachment and ball joint's center of rotation; $l_{springs}$ = distance between the spring attachment point to the ball joint's center of rotation

Considering the state of equilibrium, the cable force F_{cable} can be calculated as:

$$F_{cable} * l_{cable} * \sin\alpha - F_{springs} * l_{springs} * \sin\beta = 0 \tag{14}$$

$$\Leftrightarrow \; F_{cable} * l_{cable} * \sin\alpha = F_{springs} * l_{springs} * \sin\beta \tag{15}$$

$$\Leftrightarrow \; F_{cable} = F_{springs} * \frac{l_{springs}}{l_{cable}} * \frac{\sin\beta}{\sin\alpha} \tag{16}$$

The distance $l_{cable} = 42.9\,mm$ between the cable attachment point to the ball joint's center of rotation, the distance $l_{springs} = 25.1\,mm$ between the springs attachment point to the ball joint's center of rotation as well as the angles α and β can be derived from the Creo-Model. Because the maximum control force is required to keep the device in its open-palm position, this configuration needs to be considered to calculate the maximum control cable force F_{max}. Consequently, angle $\alpha = 140°$ and angle $\beta = 130°$. Lastly, the force $F_{springs}$ exerted by the springs is solely missing to calculate the maximum control cable force F_{max}. The spring force $F_{springs}$ can be generally calculated as:

$$F_{springs} = F_1 + R * (l_2 - l_1) \tag{17}$$

In this equation R represents the spring constant, l_1 the springs installation lengths and l_2 the current spring lengths. Furthermore, F_1 corresponds to the pretension of the springs when installed. It equals the sum of the spring's pretension due to manufacturing F_0 and the installation pretension caused by the spring installation length l_1 differing from its relaxation length l_0: $R * (l_1 - l_0)$. This leads to

$F_1 = F_0 + R * (l_1 - l_0)$. When implementing this information in Equation 17, it changes to:

$$F_{springs} = F_0 + R * (l_1 - l_0) + R * (l_2 - l_1) \quad (18)$$
$$\Leftrightarrow F_{springs} = F_0 + R * ((l_1 - l_0) + (l_2 - l_1)) \quad (19)$$
$$\Leftrightarrow F_{springs} = F_0 + R * (l_2 - l_0) \quad (20)$$

Gutekunst + Co. KG's tension spring *Z-111I* has the pretension $F_0 = 5.411\,N$, the spring rate $R = 2.02\,\frac{N}{mm}$ and the relaxation length $l_0 = 43.3\,mm$. Since two springs are applied in the model, the spring rate value and the pretension value doubles. With the maximum spring length of $l_2 = 70.4mm$, the spring force $F_{springs}$ in the open-palm grip equals:

$$F_{springs} \approx 120.16\,N$$

With this information Equation 16 can be calculated leading to a maximum control cable force F_{max} of:

$$F_{max} \approx 120.2\,N$$

Since this values is less than 140 N, it can be confirmed, that below-elbow amputees are potential users to operate the designed mechanism. Moreover, even above-elbow amputees should be able to operate the system since the estimated maximum cable force is also below 138 N - the maximum force this user group can apply as derived from measurements conducted by C. L. Taylor [4] [3].
However, since the finger mechanic will still be added to this one control cable of the designed mechanism, the maximum operation force will even further increase. Consequently, it still has to be proven in practice, if both potential user groups will finally be able to operate the system.

Pinch Forces

To have an objective comparison of the the pinch forces a VO-hand can conduct, the devices are generally compared regarding their pinching forces at an opening width of 10 mm, 20 mm and 30 mm. Hence, these pinching forces will be estimated in the following by considering the force acting on the thumb finger tip.
The pinch force F_N depends on the spring force $F_{springs}$ as visualized in Figure 29.

Considering the equilibrium state when the hand is fully closed, the pinch force F_N can be derived as:

$$F_N * l_{tip} - F_{springs} * sin\beta * l_{springs} = 0 \quad (21)$$
$$F_N = F_{springs} * sin\beta * \frac{l_{springs}}{l_{tip}} \quad (22)$$

The finger length l_{tip} and the distance $l_{springs}$ of the spring attachment to the ball joint's center of rotation are known values. However, the force $F_{springs}$ exerted by the retraction springs on the thumb as well as the angle β of the force at the different opening widths are unknown. Since the spring force $F_{springs}$ in turn depends on the spring elongation l_n, which is also unknown, three steps are required in order to calculate the pinch forces F_N at the different opening widths:

1. Calculate the spring elongation l_n at the different opening widths

2. Calculate the spring force $F_{springs}$ at the different opening widths

3. Calculate the pinch forces F_N

[3] The derivation of the maximum control force of an above-elbow amputee is comparable to the derivation of the control cable force of below-elbow amputees as described in Section 2 However, since above-elbow amputees most often apply shoulder shrug for prosthetic control, the derivation was based on the force value of 276 N, which can be reached by means of shoulder shrug [4].

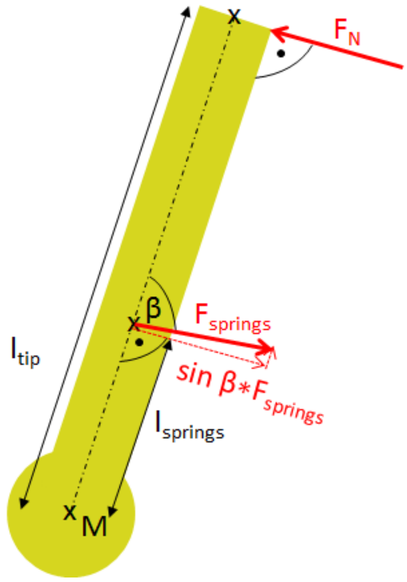


Figure 29: Deviation of the pinch force F_N by considering the equilibrium state of the forces acting on the thumb to keep the hand closed with F_N = pinch force; $F_{springs}$ = spring force; l_{tip} = length of the thumb; $l_{springs}$ = distance between the attachment of the springs and ball joint's center of rotation

Spring elongation l_n at the different opening widths

By means of Figure 30 the elongation of the springs at the different hand opening width of 10 mm, 20 mm and 30 mm can be derived.

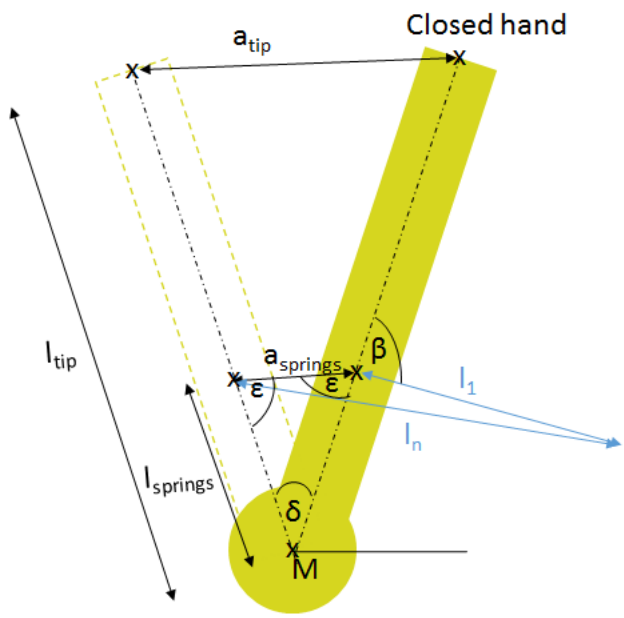


Figure 30: Deviation of spring elongation l_n when moving the thumb to a particular opening width a_{tip} with $a_{springs}$ = distance the spring attachment point is moved, l_{tip} = length of the thumb, $l_{springs}$ = distance between spring attachment and ball joint's center of rotation

When applying the law of cosines, the spring elongation l_n at a specific opening width can be calculated as:

$$l_n^2 = a_{springs}^2 + l_1^2 - 2 * a_{springs} * l_1 * \cos(\epsilon + 180° - \beta) \tag{23}$$

$$\Rightarrow l_n = \sqrt{a_{springs}^2 + l_1^2 - 2 * a_{springs} * l_1 * \cos(\epsilon + 180° - \beta)} \tag{24}$$

In this equation l_1 represents the initial elongation of the spring, β the angle of force application during lateral or opposition grip and a_{spring} the displacement of the springs attachment point. Following the second intercept theorem, the displacement a_{spring} can be calculated as:

$$\frac{a_{springs}}{a_{tip}} = \frac{l_{springs}}{l_{tip}} \tag{25}$$

$$\Leftrightarrow a_{springs} = \frac{l_{springs}}{l_{tip}} * a_{tip} \tag{26}$$

Herein $l_{springs}$ is the distance from the springs' attachment point to the ball joint's center of rotation, l_{tip} the finger length and a_{tip} represents the different opening width. When inserting Equation 26 in Equation 24, it changes to:

$$l_n = \sqrt{(\frac{l_{springs}}{l_{tip}} * a_{tip})^2 + l_1^2 - 2 * \frac{l_{springs}}{l_{tip}} * a_{tip} * l_1 * \cos(\epsilon + 180° - \beta)} \tag{27}$$

Consequently, solely the angle ϵ is missing to solve the equation. It can be calculated as:

$$\epsilon = (180° - \delta) : 2 \quad \text{with} \quad \delta = \arccos(1 - \frac{a_{tip}^2}{2 * a_{springs}^2}) \tag{28}$$

$$\Rightarrow \epsilon = \frac{180° - \arccos(1 - \frac{a_{tip}^2}{2 * a_{springs}^2})}{2} \tag{29}$$

When implementing Equation 29 in Equation 27 it change to:

$$l_n = \sqrt{(\frac{l_{springs}}{l_{tip}} * a_{tip})^2 + l_1^2 - 2 * \frac{l_{springs}}{l_{tip}} * a_{tip} * l_1 * \cos(\frac{180° - \arccos(1 - \frac{a_{tip}^2}{2 * (\frac{l_{springs}}{l_{tip}} * a_{tip})^2})}{2} + 180° - \beta)} \tag{30}$$

With $l_{springs} = 25.1\,mm$, $l_{tip} = 100\,mm$, $a_{tip} = [10\,mm; 20\,mm; 30\,mm]$, $\beta_l = 75°$ (for lateral grip) and $\beta_o = 82.5°$ (for opposition grip) as well as $l_{1,l} = 46.6\,mm$ (for lateral grip) and $l_{1,o} = 48.6\ mm$ (for opposition grip) the spring elongation can be calculated. One obtains:

- when starting from the lateral grip:

$$l_{n,l} \approx \begin{cases} 49.1\,mm & \text{for} \quad n = 10\,mm \\ 51.6\,mm & \text{for} \quad n = 20\,mm \\ 54.1\,mm & \text{for} \quad n = 30\,mm \end{cases}$$

- when starting from the opposition grip:

$$l_{n,o} \approx \begin{cases} 51.1\,mm & \text{for} \quad n = 10\,mm \\ 53.6\,mm & \text{for} \quad n = 20\,mm \\ 56.1\,mm & \text{for} \quad n = 30\,mm \end{cases}$$

Spring force $F_{springs}$ at the different opening widths
With the just determined spring elongations l_n, the pretension $F_0 = 5.411\,N$, the spring rate $R = 2.02\,\frac{N}{mm}$ and the relaxation length $l_0 = 43.3\,mm$ the spring forces $F_{springs}$ for the different opening width can be calculated as:

$$F_{springs} = 2 * F_0 + 2 * R * (l_n - l_0) \tag{31}$$

One obtains as spring forces $F_{springs}$ for the different opening width,

- when starting from the lateral grip:

$$F_{springs,l} \approx \begin{cases} 34.1\,mm & \text{for} \quad n = 10\,mm \\ 44.2\,mm & \text{for} \quad n = 20\,mm \\ 54.4\,mm & \text{for} \quad n = 30\,mm \end{cases}$$

- when starting from the opposition grip:

$$F_{springs,o} \approx \begin{cases} 42.3\,mm & \text{for} \quad n = 10\,mm \\ 52.4\,mm & \text{for} \quad n = 20\,mm \\ 62.4\,mm & \text{for} \quad n = 30\,mm \end{cases}$$

Pinch force F_N at the different opening widths
When considering a pinch force at a particular hand opening width, Equation 22 changes to:

$$F_N = F_{springs} * \sin\beta_n * \frac{l_{springs}}{l_{tip}} \tag{32}$$

Herein β_n describes the angle of the spring force at a particular opening width as illustrated in Figure 31.

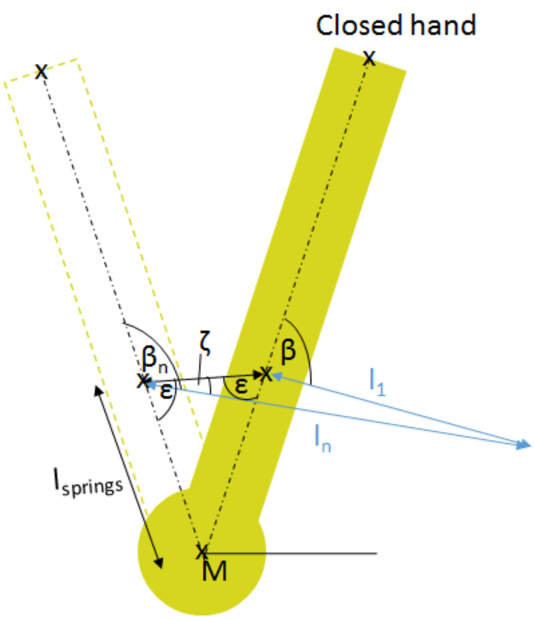


Figure 31: Deviation of the current angle β_n of the spring force

It can be calculated as:

$$\beta_n = 180^\circ - \epsilon - \zeta \tag{33}$$

with:

$$\epsilon = \frac{180^\circ - \arccos(1 - \frac{a_{tip}^2}{2 * a_{springs}^2})}{2}$$

and

$$\frac{\sin\zeta}{l_1} = \frac{sin(\epsilon + 180^\circ - \beta)}{l_n}$$
$$\Leftrightarrow \; sin\zeta = \frac{l_1}{l_n} * sin(\epsilon + 180^\circ - \beta)$$
$$\Leftrightarrow \; \zeta = \arcsin(\frac{l_1}{l_n} * sin(\epsilon + 180^\circ - \beta))$$

With these equations for the angles, the pinch forces F_N for the different opening widths can be calculated. One obtains as pinch forces F_N for the different opening widths:

- when starting from the lateral grip:

$$F_{N,l} \approx \begin{cases} 8.3\, mm & \text{for} \quad n = 10\, mm \\ 10.7\, mm & \text{for} \quad n = 20\, mm \\ 13.2\, mm & \text{for} \quad n = 30\, mm \end{cases}$$

- when starting from the opposition grip:

$$F_{N,o} \approx \begin{cases} 10.5\, mm & \text{for} \quad n = 10\, mm \\ 13.0\, mm & \text{for} \quad n = 20\, mm \\ 15.5\, mm & \text{for} \quad n = 30\, mm \end{cases}$$

Generally higher pinch force values were estimated for the opposition grip compared to the the lateral grip. With the thumb finger tip being moved about 10 mm from a closed hand position, a pinch force of 8.3 N was calculated for the lateral and of 10.5 N for the opposition grip. A pinch force of 10.7 N could be predicted for the lateral grip and of 13.0 N for the opposition grip, when the thumb finger tip is moved about 20 mm. Pinch forces of 13.2 N for the lateral grip and of 15.5 N for the opposition grip were estimated in case of the thumb finger tip being moved about 30 mm.
The differences in the obtainable pinch forces reveal, that the retraction springs have a higher pretension in the opposition grip than in the lateral one. This could be adapted by shifting the spring mounting attached to the palm dummy in radial direction. Because a higher grip strength is more often required in an opposition grip rather than a lateral grip, the current configuration of achieving higher forces in the opposition grip could present a nice feature for a final design.

Mass

Apart from the mathematical estimated model properties, the mass of the device was actually measured. The mechanism without the base plate weights 372 g. This is way higher than the maximum mass value determined in the design requirements (207 g). However, in the design requirements solely the mass of the mechanism, which would replace the motors of the Michelangelo Hand, was referred to. Consequently, the Michelangelo finger and the hand chassis, should not be considered when determining the mass of the concept. Even though in this case the mass reduces to 262 g, the achieved magnitude is not satisfying compared to the one set in the requirements. However, the goal of this study was to present a functional model rather than an actual prototype of the design. Therefore, the focus of this study was put on a working mechanism rather than a lightweight design. The model, though, still bears high potential to be optimized with respect to its mass. First of all, it comprises redundant material (e.g. the palm dummy being constructed as a solid component or the solid pathway component), which needs to be eliminated. Moreover, parts of the mechanism (e.g. the ball joint bearing) need to be resized, whereby the mass will slightly be reduced. Lastly, a lightweight design is an important criterion to be considered, when selecting the proper materials for the final components.

All estimated and measured hand properties are summarized in Table 9.

Table 9: Estimated properties and measured mass of the manufactured model

Properties		**Value**	
		Lateral grip	**Opposition grip**
Max. Opening Width [mm]		102.3	97.8
Max. Cable Excursion [mm]		43.7	41.9
Max. Cable Force [N]		120.2	
Pinch Force [N] at	10 mm	8.3	10.5
	20 mm	10.7	13.0
	30 mm	13.2	15.5
Mass [g]		262 g	

8.2. Comparison to the Michelangelo Hand

So far, it could be illustrated, that the grip type of the developed mechanism can be varied between a lateral and an opposition grip (Figure 25). Furthermore, some properties of the two hand grips habe been estimated (Table 9). In the following, it will be investigated, how well the developed device approximates the functionality of the Michelangelo Hand, to which the designed mechanism is considered to offer a body-powered alternative to in the long run.
By means of the CAD-files the designed devices can be compared to the Michelangelo Hand regarding its size and its thumb positions. Exemplarily, both hands are presented in Figure 32 in their lateral grip position (standard view (left) and side view (right)).

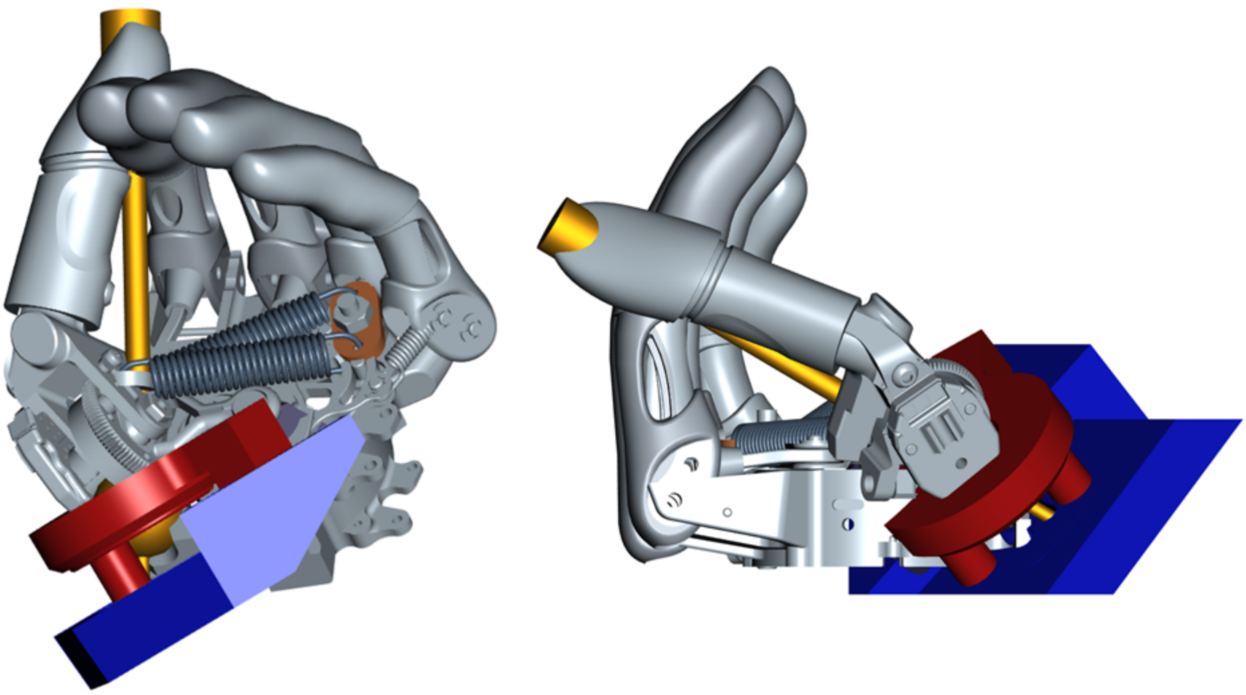


Figure 32: Comparison of the developed device and the Michelangelo Hand conducting the lateral grip by means of CAD-files regarding the alignment of the thumb finger tips, the longitudinal axes of the thumbs and the size of the complete devices; standard view of the devices (left) and side view of the devices(right)

The two hands shown in Figure 32 seem to be superposable. A similar view is received with both devices conducting an opposition grip. Solely a part of the solid component, in which the pin pathway is milled, and the ball joint bearing protrude from the chassis of the Michelangelo Hand. The ball joint and the retraction springs can give the impression of being part of the Michelangelo Hand. The toggle and its resetting system even fully disappear in the Michelangelo Hand.
In both grip types the thumbs penetrate each other at their distal part to finally, have their designated finger tips coincide. Yet, the distal longitudinal axis of the Michelangelo thumb and the longitudinal axis of the thumb of the new designed device measure a deviation of 16.3° in both grip types (Finger 33). This deviation is more than three times the limit of ±5° as defined in the requirements and hence not acceptable. This large angular deviation is mainly attributed to the Michelangelo thumb being constructed with a constant flexion in its IP, which was not yet implemented in the developed mechanism. When in the lateral grip the alignment of the thumb was adjusted to the corresponding one of the Michelangelo thumb by implementing a constant flexion in its IP, the axes of both thumbs matched perfectly as illustrated in Figure 33. The validation of the axes' alignment in the opposition grip yet still revealed a deviation angle of 4.8°. This deviation, in turn, can be attributed to the thumb's drift. As long as the drift of the thumb still leads to a natural appearance, a deviation between the thumb axis of the new developed mechanism with respect to the one of the Michelangelo thumb less than the limit of 5° is acceptable.

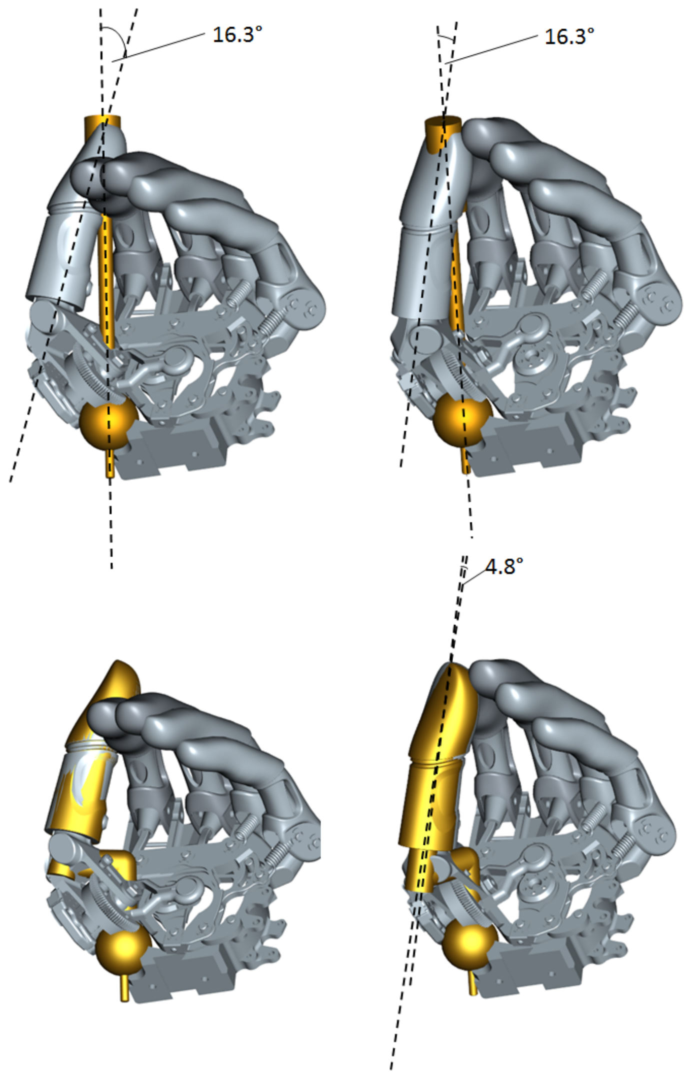


Figure 33: Influence of a thumb with preflexed IP on the deviation angle between the longitudinal axes of the thumb of the designed mechanism and the Michelangelo Thumb.

How similar both devices perform in practice is displayed in Figure 34. Here both hands laterally pinch a business card (top), hold a pen with an opposition pinch grip (middle) or a small bottle with an opposition power grip (bottom) [4]. The resultant grip patterns appear very similar with respect to the thumb approaching the other fingers. Though, small deviations regarding the rotational orientation around the thumbs longitudinal axis can be seen in the opposition grips (Figure 34 (middle) and (bottom)).

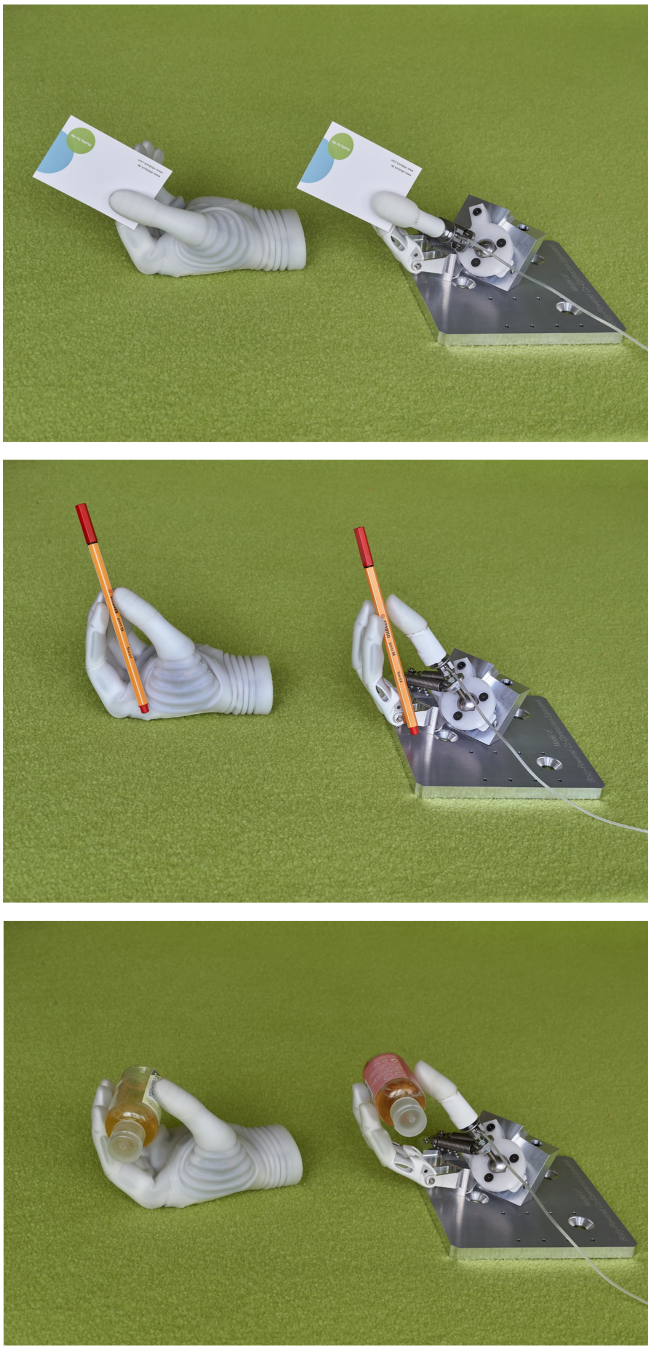


Figure 34: Comparison of the developed device and the Michelangelo Hand by means of manufactured models in practice regarding the lateral pinch grip (top), the opposition pinch grip (middle) & the opposition power grip (bottom)

[4] A lateral power grip could not be captured since in this grip type also the ring and the small finger would have been required to hold the object in position.

8.3. Verification of the Design Requirements

So far, the functionality of the designed mechanism could be presented and some properties estimated. In Table 10, it will be compared, whether and to what degree the designed mechanism fulfills the defined design requirements. Requirements marked with ✓ are met by the designed mechanism. The ❍-symbol illustrates, that the device bears the potential to fulfill this requirement in case small adaptations are conducted. Requirements, which could not yet and which are not expected to be realized in the futuare are marked with ✗. In case a requirement is not applicable anymore or it cannot yet be evaluated with the current design status, it is indicated with *n/a*.

Table 10: Verification of the developed mechanism meeting the design requirements and evaluation of the degree of satisfaction as completely fulfilled (✓), partially fulfilled (❍), not fulfilled (✗) or not applicable (n/a); color coding represents the importance of the requirement to be fulfilled: must (red), should (yellow), wish (green)

	No.	**Requirement**	**Degree of Satisfaction**	**Explanation**
Function	100	With the mechanism the grip type must be changeable	✓	A body-powered prosthetic VO-hand was developed, with which a lateral as well as an opposition grip can be conducted. When the control cable is operated, the hand gets initially opened, at what the thumb is moved to its open-palm position. In case force application is continued despite the hand having achieved its maximum open position, the grip type gets switched.
	110	With the mechanism a lateral and an opposition grip must be achievable	✓	
	111	The lateral and the opposition grip must either be VO or VC	✓	
	112	The lateral and the opposition grip could each be switched between being VO and VC	✗	
	113	The movement into the lateral and the opposition grip should appear natural	❍	When the grip type is changed, the thumb mimics the circumduction movement of the physiological thumb. However, a small spin is to be recognized, which can appear unnatural. This has to be further investigated and possibly improved.
	114	The thumb positions achieved with the mechanism should match the positions of he Michelangelo thumb for the corresponding grip within a limit ± 5°	❍	So far a large deviation angle of 16.3° was determined between the longitudinal axes of the thumb of the developed mechanism and of the Michelangelo thumb. However, by implementing a thumb, which comprises the same preflexion in its IP as the Michelangelo thumb, the maximum deviation angle can be reduced to 4.8°.

Continuation of Table 10: Verification of the developed mechanism meeting the design requirements and evaluation of the degree of satisfaction completely fulfilled (✓), partially fulfilled (❍), not fulfilled (✗) or not applicable (n/a)

	No.	Requirement	Degree of Satis-faction	Explanation
	115	The hand opening width should reach at least 80 mm	✓	When control force is applied, the thumb moves from its currently activated grip towards the open-palm grip, in which the thumb is fully abducted in radial direction and lies in the palmar plane with the remaining fully extended fingers. Consequently, the designed device even simulates the physiologically, maximally opened hand position. Following the definition of the opening width of commercially available VO-hands, a distance of about 117.5 mm could be measured between the thumb and index finger tip. To achieve this maximally opened position, the thumb finger tip has to be moved about 102.3 mm from the lateral grip and 97.8 mm from the opposition grip. Based on this, an minimum opening width of 80 mm can be guaranteed.
	116	With the mechanism a pinch force of ≥ 20 N should be achievable in the lateral and in the opposition grip	✓	The maximally achievable pinch force was estimated to be 23 N.
	120	With the mechanism grip types with the thumb in any position of the circumduction movement of a physiological thumb could be conducted	✗	Due to the concept being restricted to a defined pathway, a complete circumduction movement cannot be realized.
Control	200	The mechanism must be controlled by body motion(s)	✓	In the designed mechanism the same control cable is operated to open the VO hand and to change the grip type. Since the mechanic of the fingers is intended to be connected to the cable currently solely attached to the thumb, the final hand only requires in total one control cable. Consequently, *Otto Bock*'s standard harness *21A36=1* can be used to manipulate the designed mechanism.
	210	The mechanism must be activated by body motion(s)	✓	
	220	The mechanism should be controlled with a harness	✓	
	221	The mechanism could be controlled by Otto Bock's bandage 21A36=1 for below-elbow amputations	✓	
	222	Any changes required to the harness should prevent the user and his/her clothing from any damages	n/a	Solely the already existing control cable is required.
User Group	300	The mechanism must be usable by unilateral below-elbow amputees	✓	For the designed mechanism a maximum cable force of 120.2 N could be estimated. Furthermore, to switch from the lateral grip into an opposition one, a cable excursion of maximally 43.7 mm is required. To conduct the reversed grip type switch, the amputee solely needs to elongate the cable by 41.9 mm. Based on these estimations, the mechanism can be applied by below-elbow amputees.
	310	The mechanism should be controlled with a reasonable amount of force	✓	
	311	The mechanism should be manipulated with a tension force of ≤ 140 N	✓	
	320	The mechanism should be controlled with reasonable amount of cable excursion	✓	
	321	The mechanism should be manipulated with a cable excursion of ≤ 53 mm	✓	

Continuation of Table 10: Verification of the developed mechanism meeting the design requirements and evaluation of the degree of satisfaction completely fulfilled (✓), partially fulfilled (❍), not fulfilled (✗) or not applicable (n/a)

	No.	Requirement	Degree of Satisfaction	Explanation
	400	The mechanism could be used by bilateral below-elbow amputees	✓	Since prehension and grip type switching both are operated with the same control cable, also bilateral below- elbow amputees should be capable to use the system.
	500	The mechanism could be used by below-elbow and by above-elbow amputees	✓	In order to enable also above-elbow amputees to use the device, the maximum required control cable cannot exceed 138 N as derived from measurements conducted by C. L. Taylor [4] [5]. Since the current estimated force equals 120.2 N, the device generally bears the potential to be also used by above-elbow amputees.
Comfort	600	The usage of the mechanism should be comfortable	❍	Because the mass requirements (611 and 610 respectively) are not met yet, the device is not yet as comfortable as it could and should be.
	610	The mechanism should have a low mass	❍	The requirement is not yet achieved since the manufactured model currently weights 262 g. The manufactured model currently presents a functional model, which still requires optimization regarding its size and weight. However, it bears high potential to be optimized with respect to its mass since redundant material can still be eliminated. Moreover some components have to be resized. Furthermore, the mass can tremendously be influenced by a proper material selection, which still has to be conducted.
	611	The mass of the mechanism should be ≤ 207 g	❍	
	620	The usage of the mechanism should be as little fatigues as possible	✓	In the designed mechanism the grip type can is changed by apply an additional control force to the already maximally opened hand. The maximum control force required is estimated to be 120.2 N. Since this force value only has to be applied for a very short duration, the mechanism fulfills the requirement of being little fatigues.
	621	In case the mechanism requires a permanently applied force, the tension force should be ≤ 25 N	n/a	
	630	The usage of the mechanism could be as little mentally challenging as possible	n/a	The requirement is in the current design status not evaluable.

[5] The derivation of the maximum control force of an above-elbow amputee is comparable to the derivation of the control cable force of the below-elbow amputee as described in Section 2. Since above-elbow amputees most often apply shoulder shrug for prosthetic control, the deviation was based on the force value of 276 N, which can be reached by means of shoulder shrug [4].

Continuation of Table 10: Verification of the developed mechanism meeting the design requirements and evaluation of the degree of satisfaction completely fulfilled (✓), partially fulfilled (❍), not fulfilled (✗) or not applicable (n/a)

	No.	Requirement	Degree of Satisfaction	Explanation
	640	The usage of the mechanism could be intuitive	n/a	The requirement is in the current design status not evaluable.
	650	After having changed the grip type the control cable should move back to its default state	✓	This characteristic could not yet been validated. However, since the concept of the mechanism is based on a constant pulling direction, no cable deviation is expected.
	651	After having changed the grip type the control cable should deviate ≤ 4 mm from its default state	✓	
	652	After having changed the grip type the prostheses must be usable without readjusting the harness	✓	With the manufactured model the grip type could be changed multiple times in succession without having to adjust the system.
Appearance	700	The mechanism should be inconspicuous	❍	Currently, the size requirement (711 and 710 respectively) is not achieved yet. However, it is expected, that the device can on the long run reach the size of the Michelangelo Hand.
	710	The mechanism should be visually inconspicuous	❍	The mechanism approaches the size of the Michelangelo Hand. However, in order to actually acquire the size of the Michelangelo Hand especially the solid pathway component and the ball joint bearing of the designed mechanism need to be scaled down. Nevertheless, it is believed, that the mechanism can be adapted such, that it finally resembles the size of the Michelangelo Hand.
	711	The height the mechanism adds to the size of a standard prosthesis should be ≤ 18 mm	❍	
	720	The mechanism should be acoustically inconspicuous	n/a	The requirement is in the current design status not evaluable. However, so far no extremely loud noises were observed.
	721	The acoustic level of the mechanism should be ≤ 35 dB (A)	n/a	
Cost	800	The manufacturing costs of the mechanism should be ≤ 75 €	n/a	The requirement is in the current design status not evaluable.
Robustness	900	The mechanism should be robust	n/a	In the current design status not evaluatable. However, the mechanism is expected to meet these requirements since the mechanic does not comprise any component prone to breakage.
	910	The mechanism should be durable for ≥ 5 years	n/a	
	911	The mechanism should survive ≥ 500,000 test cycles of switching the grip type and grasping with the max. achievable pinch force	n/a	
	920	The mechanism should be temperature-resistant	n/a	
	921	The mechanism should be resistant to temperatures between -20°C and +60°C	n/a	
Transerability	1,000	The mechanism could be adapted to be used as an altering mechanism between different movements (e.g. pronation/supination and gripping)	✗	Due to the mechanism being based on a distinct pathway, the concept cannot be easily applied to switch between other prosthetic hand movements like wrist rotation and prehension

In summary, it can be stated, that the designed mechanism fulfills all critical requirements, which is why the design goal has been achieved. Beyond this, it has been presented, that the development meets some "should"- and even "could"-requirements. Moreover, small adjustments have been suggested, by which the mechanism is expected to meet all requirements apart from three "could"-requirements (the complete circumduction movement,the two-way control and the transferability).

8.4. Comparison to Commercially Available VO-Hands

In order to get an idea how well the developed mechanism is expected to perform in practice, it will be compared to other commercially available VO hands as they are described by Smit et al. in his study "Efficiency of voluntary opening hand and hook prosthetic devices, 24 years of development?" [2]. While doing so, it has to be kept in mind, that the properties of the designed mechanism are solely estimated values. Its actual performance still has to be tested especially when the mechanic of the other fingers has been coupled to the thumb control cable.
Currently commercially available prosthesis are designed immutably in an opposition grip. Consequently, the developed device surpasses the commercially available one regarding its functionality by offering the amputee to select between a lateral or an opposition grip at any time.
In order to be able to judge, which disadvantages the additional feature implemented in the development drags along, the design will be compared to commercially available VO hands with regard to its maximum opening width, its maximum cable excursion, the maximum cable force required to operate the system,the pinch forces at opening width of 10 mm, 20 mm and 30 mm and the mass (Table 11).

Table 11: Model properties in comparison to commercially available VO hands derived from [2]

VO-Hand	**Max. Opening Width** [mm]	**Max. Cable Excursion** [mm]	**Max. Cable Force** [N]	**Pinch Force** [N] at			**Mass** [g]
				10 mm	20 mm	30 mm	
Hosmer Becker Imperial	75	49	65	10	11	10	367
Hosmer Sierra	41/67	25	75	15	12	10	356
Hosmer Soft	74	38	121	15	12	12	310
RSL Steeper VO Hand	81	46	120	3	6	7	328
Otto Bock VO Hand	85	56	105	10	10	10	326
∅-Values	63	42.8	97.2	10.6	10.2	9.8	337.4
Designed Model (Lateral Grip)	102.3	43.7	120.2	8.3	10.7	13.2	262
Designed Model (Opposition Grip)	97.8	41.9		10.5	13	15.5	

- **Maximum opening width**: In contrast to the designed mechanism, commercially available VO hands are constructed immutably in an opposition grip. Consequently, the opening width of these hands is distinctly defined as the distance between the thumb and the opposing index finger or index and middle finger. The majority of the devices comprise an maximum opening width around 80 mm [2]. However, in this designed device the thumb moves from its currently activated grip towards the open-palm grip, in which the thumb is fully abducted in radial direction and lies in the palmar plane with the other fully extended fingers. Consequently, the designed device even simulates the physiologically, maximally opened hand position. Anyway, following the definition of the opening width of the other VO hands, a distance of about 117.5 mm could be measured in the open-palm grip. To achieve this maximally opened position, the thumb finger tip has to be moved about 102.3 mm from the lateral grip and 97.8 mm from the opposition grip. Based on this, an opening width of 80 mm can be guaranteed.

- **Maximum Cable Excursion**: To change from the lateral grip to the opposition one, a cable excursion of maximal 43.7 mm is required. To conduct the switch of the grip type in reverse, the amputee solely needs to displace the cable by 41.9 mm. The required cable excursions are closed to the average cable excursion (42.8 mm) of the commercially available VO hands.

- **Maximum Cable Force**: For the designed mechanism a maximum cable force of 120.2 N is estimated. The required force is similar to the ones of the *Hosmer Soft VO Hand* and the *RSL Steeper VO Hand*, which are considerably higher than the forces needed to operate the other devices described by Smit et al. [2]. Since the finger mechanic will still be added to the control cable of the designed mechanism, the maximum cable force will further increase. However, in the new design the maximum cable force refers to the force values required for the switching of the grip type during which the hand opening width has already exceeded the other ones. Thus, the maximum cable forces are not determined under the same conditions. Nevertheless, in the future it has to be evaluated, if the implemented features justify the increased required cable forces.

- **Pinch Forces**: Because of the pinching force in VO hands being highly depended on the current opening width, commercially available VO hands are generally compared by measuring the pinch force at an opening width of 10 mm, 20 mm and 30 mm. The VO hands presented in Smit et al. [2] reveal on average a pinch force of 10.6 N (at 10 mm), of 10.2 N (at 20 mm) and of 9.8 N (at 30 mm). Apart from the lateral pinch force at an opening width of 10 mm, the pinch forces of the developed design were estimated to be higher than the average values of the VO hands presented in Smit et al. [2]. Even though the lateral pinch force at an opening width of 10 mm is with 8.3 N lower then the average pinch force of available VO hands, it is more than 2.5-times higher then the pinch force of the RSL Steeper VO Hand [2].

- **Mass**: A mass of 372 g was determined for the designed mechanism, if all components apart from the base plate were taken into account. Hence, it is 5 g heavier than *Hosmer*'s *Becker Imperial*, which measures the highest mass value among the commercially available VO hands. However, the manufactured model currently presents a functional model, which still requires optimization regarding its size and weight. Since it bears high potential for optimizing it with respect to is mass, the mechanism is expected to reach a mass magnitude less than the average value (337.4 g) of commercially available VO hands in the long term.

To sum up, the developed device is expected to perform equally well compared to commercially available VO hands, but facilitates a clearly improved functionality and appearance by offering a lateral as well as an opposition grip type. However, the actual characteristics of the mechanism still have to be proven in practice with a complete hand as prototype.

9. Prospects

So far only a functional model of the mechanism was presented. The design still requires some adaptations and optimizations regarding its size and weight in order to qualify as an actual prototype. For example, the ball bearing and the solid pathway component need to be resized or a well-wrought material selection must still be conducted. Furthermore, the geometry of the toggle and its relation to the thumb guiding pin should be revised, such that the toggle tip always distinctly passes the system's dead-center position before the thumb guiding pin moves to the newly reached pathway branch.

Apart from the already presented suggestions for improvements, two additional characteristics need to be elaborated and added to the device in order to achieve an acceptable prosthetic hand: first of all the routing of the thumb's control cable needs to be revised since the cable currently stretches from the dorsal side of the thumb, which is highly conspicuous. Secondly, the mechanic of the remaining fingers needs to be developed, so that they can be actively manipulated with the same control cable as the thumb.
In the following, for each characteristic a concept is presented, how it could potentially be realized in the body-powered alternative to Otto Bock's Michelangelo Hand.

9.1. Potential Thumb Control Cable Guiding

There are two major characteristics, which have to be considered for the routing of the thumb's control cable: first of all, the cable needs to run from its fixation on the thumb in proximal direction. Only if it stretches along the longitudinal axis of the arm towards the shoulder, it can be applied to the standard harness of below-elbow amputees. Secondly, the control cable force required to operate the thumb's movement depends on the distance between the mounting of the control cable on the thumb and the center of rotation of the ball joint. The further away from the ball joint's center of rotation it is attached, the bigger the lever the control cable force acts on becomes and thus, reduces the force the amputee has to apply to operate the prosthesis. In order to achieve an acceptable maximum control force while having the cable orientated in proximal direction, the cable mounting was positioned above the ball joint in an distance of approximately 47 mm. With the current configuration an acceptable maximum cable force of 120.2 N could be estimated. However, owing to the current location, the control cable will exit the prosthetic cosmesis on the dorsal side of the thumb, which will appear unnatural and be highly conspicuous. Desirably, the control cable is hidden within the cosmesis. This is generally possible by attaching the cable to the thumb guiding pin below the ball joint rather than to the thumb shaft itself. In contrast to the thumb shaft, the thumb guiding pin needs to be pulled in distal direction towards the palm dummy in order to move the thumb towards its open-palm position. Consequently, a deflection pulley is required to ensure, that the cable can still be operated from the proximal direction. Moreover, the distance between the cable attachment and the ball joint's center of rotation is decreased, when shifting the cable below the ball joint, due to a reduced installation space. In order to prevent the required control force from increasing, the force transmission ratio between the control cable force and the pulling force acting on the thumb guiding pin should be alternated. This can be accomplished by utilizing a movable pulley as illustrated in Figure 35. Here the cable is fixed to the palm dummy rather than to the thumb itself. To the thumb, in turn, the movable pulley is attached, through which the control cable is guided. A fixed pulley mounted to the palm dummy then redirects the control cable in the desired proximal direction. Due to this configuration, the force, required by the amputee to operate the system, remains equal despite the decreased distance between cable attachment to the thumb guiding pin and the ball joint's center of rotation.

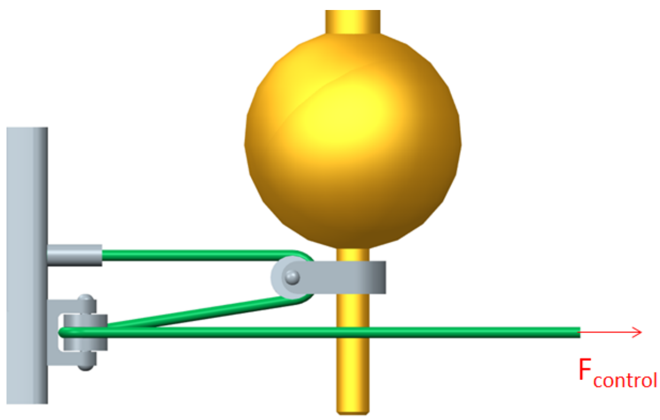


Figure 35: Potential thumb control cable guiding: The thumb cable is located below the ball joint. It is attached to the palm dummy and stretches to a movable pulley fixed on the thumb guiding pin. A deflection pulley mounted to the palm dummy directs the cable in proximal direction.

This is a possible solution, how the control cable attachment can be moved below the ball joint's center of rotation without increasing the cable forces. However, with the presented configuration the cable excursion will extend.

9.2. Potential Finger Mechanism

The fingers of the Michelangelo Hand can adapt to the shape of the object to be grasped. This characteristic is highly desirable in order to increase the grip stability especially when manipulating irregular shaped objects. Recent research focuses on realizing this feature in body-powered VC hands by means of differential coupling. Here the force transmission between adjacent fingers is adapted depending on the forces opposing each finger. As soon as one finger is in contact with an object, further applied force is shifted to the other fingers enabling them to continue flexing. The principle of differential coupling can also be transferred to a VO hand as illustrated in Figure 36.

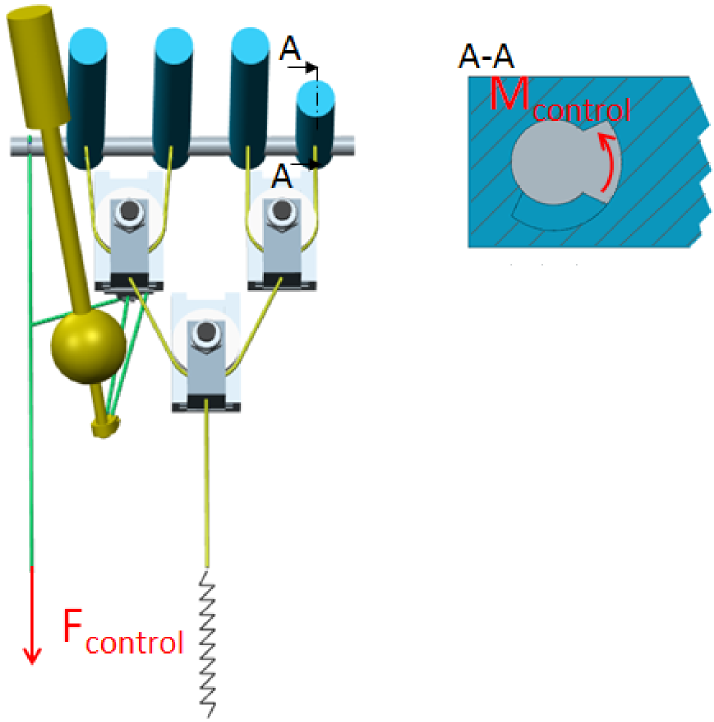


Figure 36: Potential finger mechanic: The thumb control cable fuses with the finger control cable to one main control cable, so that the hand opening is controlled solely with one cable. When the main control cable is tensioned, it causes the shaft, on which the fingers are positioned on, to rotate counterclockwise. The fingers are pushed by entrainers to follow this rotation. The finger of the hand are differential coupled by means of floating pulleys, by which the closing of the hand is conducted in an adaptable manner. When the fingers are pulled by a spring to rotate clockwise, they push against the entrainers and hence, dragg the finger shaft to follow the motion. The entrainers are visual in sectional plane A-A.

Figure 36 shows a VO-hand, in which all fingers apart from the thumb are positioned on the same shaft. To this shaft a right-wound cable (green cable) is attached, so that the tensioning of the cable leads to a counterclockwise rotation of the shaft. Thereby it pushes the fingers by means of entrainers (sectional plane A-A) to follow its rotational direction leading to the opening of the hand.
Closing of the hand, on the contrary, is initiated by means of a spring. The fingers and the spring are differentially coupled by means of three floating pulleys each driving a separate tendon (yellow cables). The pulleys are arranged on two levels; the pulley on the first level is connected by means of a tendon (yellow cables) to the tension spring of the fingers. It guides the tendon, which couples the two pulleys on the second level. Each pulley on the second level, in turn, directd a tendon (yellow cables), which

links two adjacent fingers. When the amputee stops to tension the control cable (green cable), the preloaded tension spring of the fingers is the driving force to close the hand. For this, it pulls at the tendon attached to the pulley on the first level, whereas the pulley is moved in proximal direction. Hereby, it drags the pulleys on the second level along. Their movement in proximal direction, in turn, cause the fingers to rotate clockwise and thus, the hand to close. By doing so, the fingers push against the entrainers (sectional plane A-A) causing the finger coupling shaft to follow their movement.
The transmission of the spring force to each finger adapts in case a finger contacts an object and hence, cannot rotate any further. Due to changes in the "floating-wheels"-configuration, the remaining fingers can still continue to rotate counterclockwise as illustrated in Figure 37.

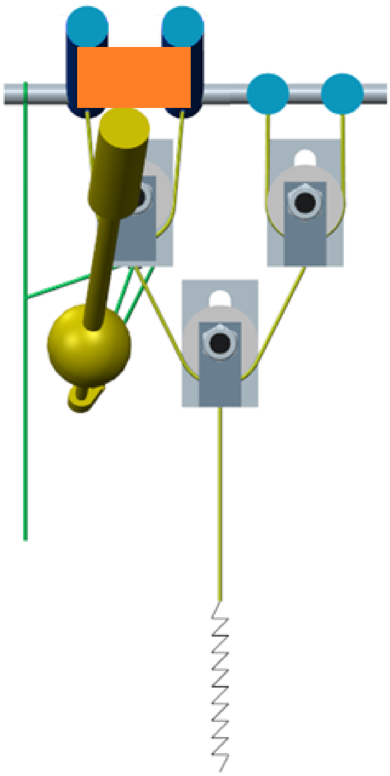
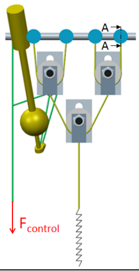
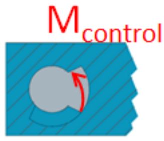
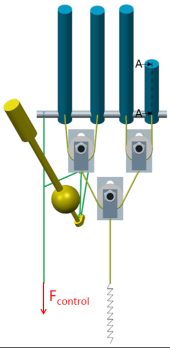
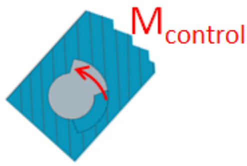
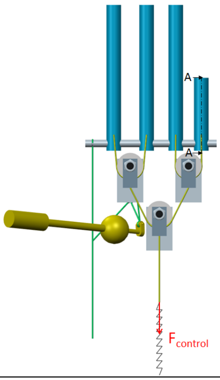
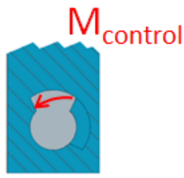
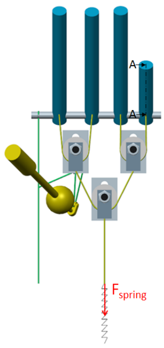
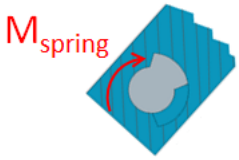
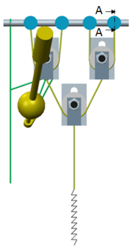


Figure 37: Illustration of the adaptive finger realized by means of differential coupling

In the configuration shown in Figure 37 the index and the middle finger contact an object, by which they are prevented to flex further. The ring and the little finger, on the contrary, do not experience an opposing force. They are capable to continue their flexion motion due to a force adaptation on the first pulley level. When the pulley of the first level is pulled by the tension spring of the fingers in proximal direction, it usually exerts equal force to both pulleys on the second level and hence, drags them along. However, due to the resistant force acting on the index and the middle finger, the adjacent second level pulley is prevented to follow the movement of the pulley on the first level. In this case, the pulley on the first level adapts its force application by starting to rotate. Consequently, in addition to its translational motion in proximal direction the first level pulley rotates. Hence, the ring and the middle finger can continue to flex even though motion of the index and middle finger is blocked.

To couple the movement of the fingers with the thumb movement, the control cable of the shaft and the thumb's control cable merge to a main one, which is attached to the harness. In the following a cycle of opening the hand, switching the grip type and closing the hand will be depicted in more detail for the proposed VO-hand. Table 12 comprises a visual illustration of the different steps showing the complete finger mechanic (middle) and a cut through the little finger (right). Here the designed thumb switching mechanism is reduced to its cable mounting for illustration purposes.

Table 12: Step-by-Step Illustration of Grisp Type Variation Including the Potential Finger Mechanism

Description	Mechanism	Finger Cut A-A
Lateral grip		
Opening of the hand		
Open-palm grip		
Closing of the hand		
Opposition grip		

- **Lateral grip**: Starting from the lateral grip, the thumb is located in its lateral grip position. Since the remaining fingers are in their flexed position, the finger coupling shaft is turned to its clockwise end position, the floating pulleys are moved to their proximal end positions and the tension spring of the fingers is fully relaxed.
- **Hand opening**: In order to open the hand, the amputee applies force to the main control cable (green). Thereby, the thumb is moved towards its open-palm position. Proportional to this movement the retraction springs of the thumb (not shown) are getting tensioned. Since the main control cable (green) is right-wound around the shaft coupling the fingers, the shaft gets rotated in counterclockwise direction when the control cable is tensioned. Hereby the entrainers push the fingers, so that they follow the counterclockwise rotation. The hand gets opened. On doing so, the tendons attached to the fingers pull the pulleys on the second level in distal direction. Since the tendon passing the pulley on the first level is fixed to the pulleys on the second level, the pulley on the first level is dragged along in the distal direction. The tension spring of the fingers is stretched proportionally to the translation of the pulley it is fixed to.
- **Open-palm grip**: As soon as the open-palm grip is reached additional force applied to the cable initiates the change of the grip type. Here the thumb's guiding pin gets transferred by means of the toggle to the opposition pathway branch. The additional force applied to the control cable causes also the finger shaft to rotate further in counterclockwise direction, by which the fingers are slightly hyperextend. All pulleys have been moved to their distal end position and the tension spring of the fingers got maximally preloaded.
- **Hand closing**: When the amputee releases the control force, the closing of the hand is conducted by means of passive elements. The retraction springs of the thumb (not shown) move the thumb towards its opposition grip position. Simultaneously, the preloaded tension spring of the fingers causes the flexion of the fingers by pulling the first level pulley in proximal direction. This pulley, in turn, drives the pulleys on the second level to follow its motion. Thereby, the tendons stretching from the second level pulleys to adjacent fingers initiates the fingers to rotate clockwise. Here, the walls of the recess in the finger push against the entrainers of the finger coupling shaft, so that the shaft follows this rotation in clockwise direction.
- **Opposition grip**: The thumb has been moved to its opposition grip position. The tension spring of the fingers is fully relaxed and has pulled all pulleys to their initial proximal direction. Hence, the shaft as well as the fingers are rotated to their clockwise end position.

As described the fingers get slightly hyperextended when the grip type is changed. In case the amputee is not satisfied with this characteristic, it could be prevented by incorporating a passive element at the finger cable attachment, which compensates the additional cable tensioning required to switch the grip type.

The presented design provides the potential to be equipped with additional features, which could improve its usage even further. For example, it is recommended to incorporate an obstacle, by which the amputee is alerted that the maximum open hand position has been achieved and that the grip type will get switched, when the application of force is continued.

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III

Literature Review: “Mechanisms to control and alter multiple degrees of freedom of body-powered hand prostheses”

Abstract

Hand prostheses launched and hyped by leading upper limb prosthetic companies in the last years had all one common feature: myoelectric control. Possibly, the companies saw the potential of myoelectric prostheses satisfying most of the user wants of comfort, control and cosmesis. Compared to body-powered prostheses, myoelectric prostheses have the advantage of enabling multiple degrees of freedom (DoFs) contributing to fulfill these wants. However, body-powered prostheses also have advantages over myoelectric ones e.g. proprioceptive feedback, which could not yet been implemented in myoelectric ones in an intuitive way. Since the task remains a challenge, it might rather be more reasonable to add the feature of multiple DoFs to body-powered prostheses. Based on this idea, this literature review investigates, firstly if attempts have been made to design body-powered hand prostheses with multiple degrees of freedom and if so why they have not been successful. Secondly, it considers, if and how engineers are currently working on this issue.

An extensive literature research was conducted. From more than 540 titles considered derived from the four databases *PubMed*, *Web of Science*, *Scopus* and *IEEE Biomedical Engineering Library*. Relevant products were portrayed and analyzed according to their control principles of multiple degrees of freedom.

The records firstly revealed that over the course of time multiple attempts to design body-powered prostheses, which either facilitated multiple grasp patterns or enabled wrist motion, were made, whereby waves of publications dealing with body-powered prostheses and commercialization were identified. Even more importantly, it became apparent that the approaches applied in the past as well as present are often very similar in the way they are controlling multiple degrees of freedom. However, these approaches are mentally challenging, counterintuitive, aesthetically unpleasant or solely restricted to a small group of amputees and therefore inadequate solutions compared to the control of multiple DoFs in myolectric prostheses.

The literature review concludes with emphasizing that there still is an unsatisfied need for body-powered prostheses with multiple degrees of freedom and suggests further research in this direction. . Concretely, the author suggests to develop a mechanical switching mechanism comparable to myoelectric signals to control multiple DoFs, for which mechanism in past attempts on body-powered prosthesis illustrated in this literature review can serve as sources of inspiration.

1. Introduction

Research on the control methods of prosthetic prehension is manifold [1]. However, so far mainly two methods (body-powered and myoelectric control) gained acceptance and are applied in commercially available upper-limb prostheses. Other methods are either highly invasive (e.g. brain-computer interface or peripheral nerve interface), denied due to unaesthetic results (e.g. cineplasty), or because of being tremendously counterintuitive (e.g. foot or voice control). Even though the different control mechanism alternatives are highly interesting and might have some advantageous characteristics, this review is focused on the control mechanisms of commercially available prostheses since they have been proven functional in practice. Commercially available prosthetic components are either classified as body-powered or as myoelectric. A body-powered prosthesis typically consists of a harness, which is connected by a Bowden cable to the prosthetic terminal device (TD). In this way, the amputee uses movements of e.g. the residual limb and the contralateral shoulder to power and to control prosthetic prehension. Thus, the magnitude of prehension is determined by the range of the body movements and the power the amputee can exert. In the case of myoelectric prostheses signals of the residual stump muscles are tapped and serve as input signals for externally, electrically powered actuators.
Which prosthetic type should be applied to the amputee depends on his/her wishes, needs, life style, expectations as well as his/her physical and mental condition. Simplicity, durability, light weight and lower costs are for example characteristics of body-powered prostheses. Furthermore, they excel to facilitate extended proprioreceptive feedback by means of the control harness [1–10]. Hence, the user of a body-powered prosthesis can learn to correlate its range of body motion to the force he/she is applying and knows the prehension state (open or closed) of the hand [11] . Due to the extended proprioreceptive feedback the amputee is not required to visually monitor his prehension movement [12]. In addition, the amputee receives feedback regarding any perturbations and can adapt to the uncertain events. This improves the prosthetic control and also the identification of the amputee with the limb replacement. However, because of the body-powered prostheses being actuated by large movements of the remaining limbs, their usage might appear unnatural especially in the case of neoamputees and thus attract attention [1].
In contrast, the myoelectric control can be more inconspicous [9, 13]. Furthermore, movements with a myoelectric prosthesis can appear more natural, because they generally facilitate multiple grip types as well as additional hand motions (e.g. pronation/supination). Due to externally powered actuation, myoelectric prostheses require hardly any physical effort and sufficient gripping force is guaranteed [5, 7, 9, 13]. Nevertheless, the external power source increases the weight, the fragility and the costs (initial and maintenance) of myoelectric prostheses [5, 13–15]. Additionally, this prosthetic type lacks proprioceptive feedback [10, 13].
The short introduction of pros and cons of the two prosthetic types reveals that neither control mechanism can replace the natural hand optimally. Each control type offers a characteristic, in which it surpasses the other one. However, most of the upper-limb products launched by leading companies (e.g. Otto Bock HealthCare GmbH, Touch Bionics Inc., Steeper or Vincent Systems) in the last years were myoelectric prostheses [16–18]. The companies might have seen higher potential of myoelectric prostheses fulfilling most of the consumer wishes, which were found to be *comfort*, *control* and *cosmesis* [12, 19]. The amputees would like to have a prosthesis which is comfortable to wear, which can be controlled easily and inconspicuously and which has an appealing as well as a natural appearance [12, 20, 21].
The myoelectric feature of multiple degrees of freedom [2] (DoFs) in form of independent finger movements, the thumb being switchable between opposition and reposition or in form of wrist movements highly contributes to fulfilling these user wishes. The individual finger movements or the variable thumb positioning lead to a more anthropomorphic appearance of the device. Furthermore, multiple grip patterns can be conducted and specifically selected for a certain task. In addition to this, individual fingers

[1]Prosthetic replacements of the upper limbs are categorized as passive or active devices. The passive hands are primarily used for aesthetic reasons. Their appearance is more natural, but their functionality is either very limited or does not exist at all. If a passive prosthesis is functional, the user can solely clamp an object into it by means of the sound hand. Consequently, a passive prosthesis, if supporting any functionality, is restricted to simple holding tasks. On the contrary, active prostheses can be used to actually grasp and manipulate an object without requiring the sound hand. Since solely active prosthesis require a control mechanism for prosthetic prehension, this literature review is restricted to the active prosthetic type.

[2]the term "*multiple degrees of freedom*" used with regard to hand prostheses slightly deviates from the engineering definition as depicted in detail in Section 1

can adapt to the object to be grasped. Thus, hand movements appear more natural and a more stable grip can be accomplished.
Having an arm prosthesis which facilitates pronation/supination and/or flexion/extension of the wrist contributes tremendously to more natural motion patterns as well [13, 22]. If these DoFs cannot be performed, the amputee needs to conduct unnatural body motions with the residual limbs to compensate for them [22–24]. The compensatory motions are task-depended, but are generally executed by changed motion patterns of the elbow, the shoulder, the shoulder girdle or the torso [25–28]. Compensatory movements require greater ranges of motion of the residual articulations and thus, more physical effort than physiological movements [24, 27, 29]. Additionally, the changed body kinematics cause higher loads on the residual limbs [24, 29]. Even though the body will adapt to the new loading, it can eventually cause pain and other long-term damage [24, 27, 28, 30]. These conditions tremendously affect the quality of life of the amputees. The significance of this feature is reflected in the user design priorities. The desire of wrist and individual finger movements as well as a thumb, which can be switched between lateral or opposed position, is stated in literature repeatedly [5, 20, 21, 31–33].
Even though myoelectric prostheses can nowadays promote multiple DoFs, body-powered prostheses have the big advantage over myoelectric ones of extended proprioceptive feedback. Proprioceptive feedback is a natural sensory feedback making the body aware of the motions and positions of its parts in space as well as the forces it exerts. Body-powered prostheses can facilitate such a proprioceptive feedback in an extended way. The users of a body-powered prostheses can learn to map the range of the operating motion to the force they are applying with the prostheses. Furthermore, they know the status (open or closed) of their prosthesis at any time without having to look at the prosthesis. In contrast, users of myoelectric prostheses do not receive such an extended proprioceptive feedback and therefore, have to constantly track the movements of the prostheses visually. This continuous monitoring tremendously increases the mental load on the user of a myoelectric device [12, 32]. Multiple attempts have been made to incorporate such a sensory feedback in a myoelectric prosthesis, but so far it could not yet be realized in an intuitive way.
A prosthesis facilitating the body-powered feature of extended proprioceptive feedback in addition to the myoelectric feature of multiple DoFs would be highly advantageous for the amputee . Since the characteristics could not successfully be combined in a myoelectric prosthesis, it is conceivable to add additional DoFs to a body-powered prosthesis. Hence, this review investigates, ***if attempts have been made to design body-powered hand prostheses with multiple degrees of freedom and if so why they have not been successful***. Furthermore, it will be studied, ***if engineers are currently working on this issue and how they are trying to find a suitable solution***. It needs to be pointed out, that this review will be restricted to purely mechanical body-powered hand prosthesis leaving out body-powered prostheses with pneumatic or hydraulic assistance to narrow the number of devices. To get an idea on how multiple degrees of freedom can be successfully implemented, the control principles of the most advanced, commercially available myoelectric prostheses are illustrated in the following.
The strategies and methods to answer the previous defined research questions will be outlined in the next chapter followed by the fundamentals of the myoelectric and the body-powered control for prehension. A hand prosthesis has multiple DoFs, if it facilitates individual finger movements or a thumb being switchable between opposition and reposition leading to different grip patterns. Furthermore, wrist motion in addition to prehension also increases the number of DoFs of the prosthetic device. Both characteristics of increasing the number of DoFs are considered in this literature review. In Chapter 4 the techniques to alter grasping patterns will be examined. Then, the implementation of the wrist joint in myoelectric and body-powered prostheses will be studied in Chapter 5. Finally, current research of other possible ways to achieve multiple DoFs will be sketched. In the last chapter the devices, found to facilitate multiple DoFs, will be discussed and a conclusion will be drawn.

1.1. Definition of "multiple degrees of freedom"

In mechanics a degree of freedom (DoF) is defined as an independently controllable movement direction [34]. A point of mass in space can have six different DoFs: three translational and three rotational ones (Figure 1).

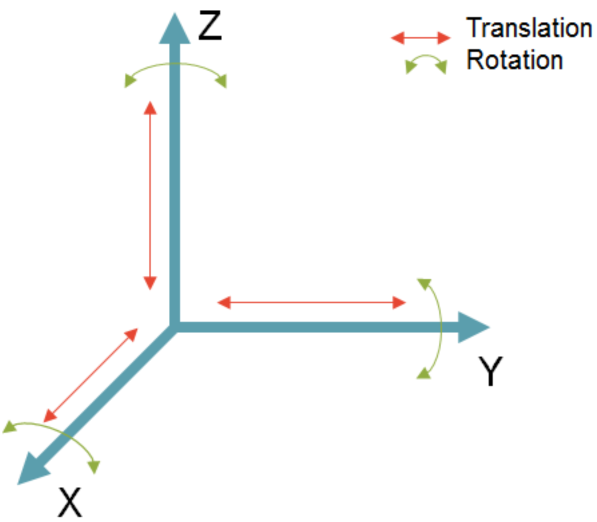

Figure 1: Possible degrees of freedom of a point of mass in space: three translational and three rotational degrees

In this literature review the term "multiple degrees of freedom" is used, if an movement can be conducted along or around a new joint axis. Ergo, the movement is not necessarily independently controlled. If a terminal device (TD) can facilitate a pinch grasp as well as a power grasp, has a thumb, which is changable between reposition and opposition, or if the prosthesis promotes wrist movement (Figure 2), it will already be phrased to supply multiple DoFs. Myoelectric hands for example are said to enable multiple DoFs. However, the amputee cannot control each joint movement individually. Instead he/she can change the hand into predefined grip patterns by giving a particular trigger signal. The control principle of multiple DoFs will be explained in more detail in Chapter 4 and 5.

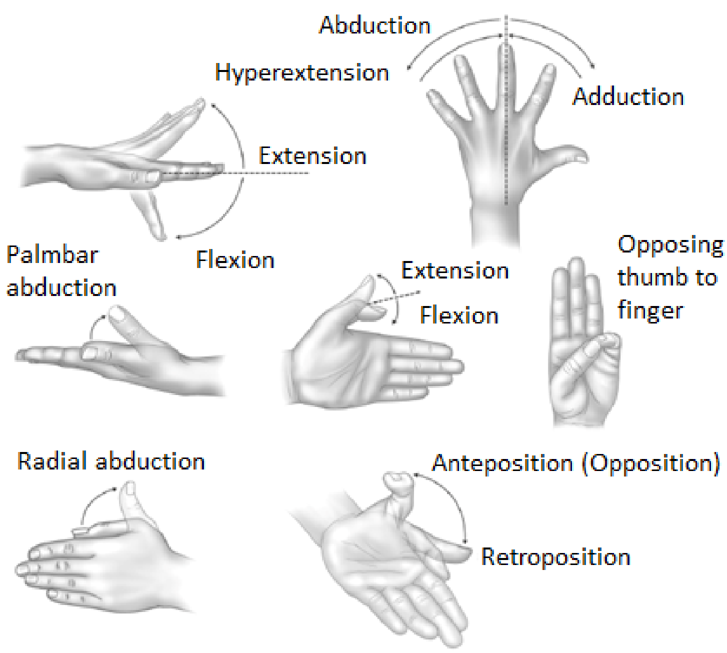

Figure 2: Examples of the term "multiple degrees of freedom" in this literature review (extracted from [35])

2. Methods

The literature review is based on a carefully conducted two-step literature research, which is presented in the following chapter. First of all a general search on the terms "*user wishes*" and "*design priorities*" with regards to upper limb prostheses was conducted. Based on thereby gathered information the research questions were elaborated.
Based on the research question formulated a more detailed literature research was carried out by means of the *Research*-function in the literature management program *Citavi 5*. This allowed the author to search within the four databases *PubMed*, *Web of Science*, *Scopus* and *IEEE Biomedical Engineering Library* simultaneously. These databases were selected since they are highly relevant in the field of Biomedical Engineering and give access to a big variety of different literature.
The following search terms/ combinations were used:

- Body-powered prosthesis / prosthetic terminal device multiple degrees of freedom / DOF;
- Control alternatives body-powered prosthesis;
- Multigrasp (body-powered) prosthesis;
- Multiarticulating body-powered prosthesis;
- Altering mechanism body-powered / hand prosthesis;
- Switching / altering / changing prosthetic grip / grip pattern / grasp;
- Multifunctional body-powered prosthesis;
- Changing thumb position of prosthesis

The search revealed 1,119 papers. Due to the usage of the *Research*-function duplicates were highlighted and easily eliminated. This reduced the number of records drastically to 750. The title of the remaining records were individually reviewed. 662 of these 750 papers were excluded due to limited relevance to the topic, e.g. not dealing with upper limb prostheses, focusing on control methods other than body-powered, addressing elbow or shoulder devices, talking about design priorities or prosthesis manufacturing. Hence, from the database search 88 records were judged to be potentially relevant for screening.
In addition to these previously outlined database search, two other sources were considered: firstly, Otto Bock's internal patent data base *infoPatent* was screened regarding prostheses with multiple degrees of freedom and 341 patents were found to be interesting. Secondly, other sources like recommended books or papers, referenced in other secondary sources, were regarded to be potentially relevant amounting up to 45 additional articles. All in all, the abstract of 474 different records were studied as visualized in a flow diagram in Figure 3.

From these 474 papers 379 were excluded, because either their abstract did not reveal the paper to present relevant information regarding body-powered prostheses with multiple DoF, the paper was written in a language other than English or German or no access was granted. Finally, 95 different references were studied. From these 95 records 36 papers were relevant enough to be included in this literature review.

Having studied those 36 records, a more detailed structure of the literature review could be elaborated. Based on the information gathered the author decided to engage in three additional search rounds.

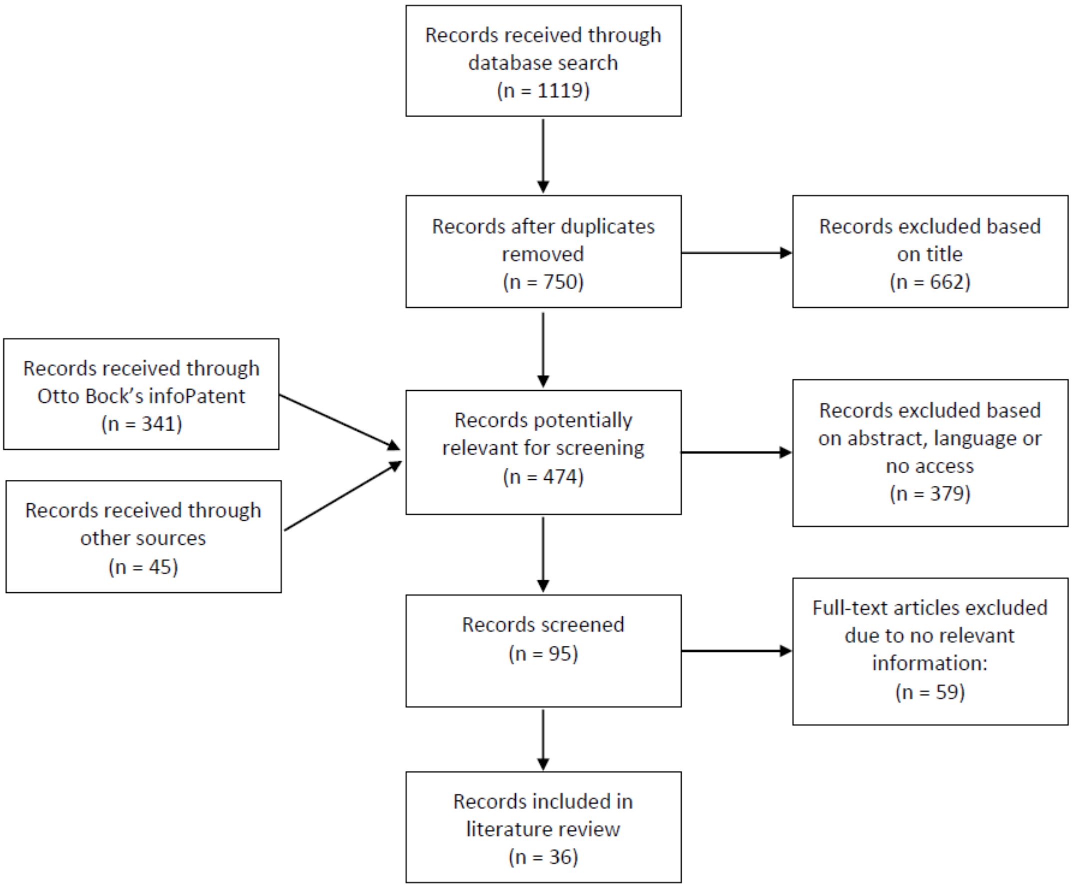

Figure 3: Flow diagram illustrating the results of the literature search regarding prostheses with mutliple DoF and the paper selection process

Firstly, considering underactuated hands, which can adapt to the shape of the object and hence, facilitate multiple grip patterns [3]. Secondly, searching for devices, which can be operated in a voluntary opening (VO) as well as a voluntary closing (VC) modus [4]. A prosthesis, which combines the VO- and the VC-mode [5], gives the amputee more control power and awareness over the whole prehension cycle. Thirdly, seeking for prosthetic wrist components since wrist motion already add DoFs to a simple body-powered hand.

Consequently, three supplementary searches were conducted: one focusing on underactuated hands, another one on VO/VC-devices and a third one on prosthetic wrists.
The following search combinations of terms were used for the underacutated hands:

- body-powered underactuated hand / terminal device

More papers regarding VO/VC-devices were searched by:

- voluntary(-)opening & voluntary(-)closing / VO & VC hand / prehensor / terminal device / gripper;

- switching modes body-powered prosthesis;

[3] A definition of "underactuation" and a more detailed description of underactuated hands will be given in Section 4.2.1.
[4] Further explanations regarding VO and VC prostheses will be described in Section 3.2 and in Section 4.2.2.
[5] In the following prostheses, which can be operated VO as well as VC, will be called VO/VC-devices.

- body-powered voluntary open prosthesis;
- body-powered voluntary closed prosthesis;
- mode selection body-powered prosthesis

In order to find more papers dealing with a body-powered wrist the following search term combinations were implemented:

- body-powered wrist flexion / extension / flexion & extension / pronation / supination / pronation & supination

The record selection processes of the three additional research rounds were comparable to the earlier described one. However, the papers, which had already been found in the earlier search, were excluded as well. The flow charts visualizing the paper selection processes can be found in Appendix A.

9 additional papers addressing underactuated hands, 15 records presenting VO/VC-hands and 7 additional papers dealing with wrist components were obtained for this literature review and added to the previous research results. All in all, information of from in total 67 different papers could be gathered and it will be presented in this literature review.

3. Basic principles of prosthetic prehension

In the following the basic principles of the two most common commercially available prosthetic control mechanisms will be presented. Since the focus of this literature review is put on hand prostheses solely transradial amputees will be considered. The basic principles for prehension are comparable for above-elbow amputees. However, transhumeral amputees miss the elbow joint as well for which an additional control mechanism is required. This will not be further elaborated.

3.1. Myoelectric prostheses

For myoelectric controlled prostheses muscle signals are recorded with electrodes attached to the skin surface of the residual limb and serve as input signals for electrical powered actuators. These muscle signals are electric potentials, which arise each time a muscle contracts [12, 14, 36].
Muscle contraction is initiated by electrical impulses of the central nervous system. These impulses are conducted via motor neurons to the motor end plates of the muscle fibers, which the motor neuron innervates. There an electric signal, the action potential, is triggered by the motor neuron and is transmitted along the muscle fibers. The action potential initiates additional chemical and mechanical processes, which finally lead to muscle contraction [36].
The sum of the individual action potentials of the fibers can be recorded by electrodes on the skin surface. Since tissue layers and external, low frequency signals disturb the records, the myoelectric signal needs to be amplified and filtered. Thus, low myoelectric signals can also be used as prosthesis control. The processed signal is transformed to a direct current potential and serves after smoothing as input signal for the prosthesis actuator. The actuator is an electric motor driving the prosthetic prehension [12, 36].
The general control scheme of a myoelectric prosthesis is illustrated in Figure 4.

Two electrodes are attached to antagonistic muscles of the residual limbs. Each electrode is responsible for one prehension mode (opening and closing) [12, 36]. For below-elbow prostheses the electrodes are usually attached to the antagonist muscles *Mm. sculus flectores carpi et digitorium* and *Mm. extensores carpi et digitorum* [36]).

There exist different ways of realizing myoelectric control. In initial attempts of myoelectric prostheses

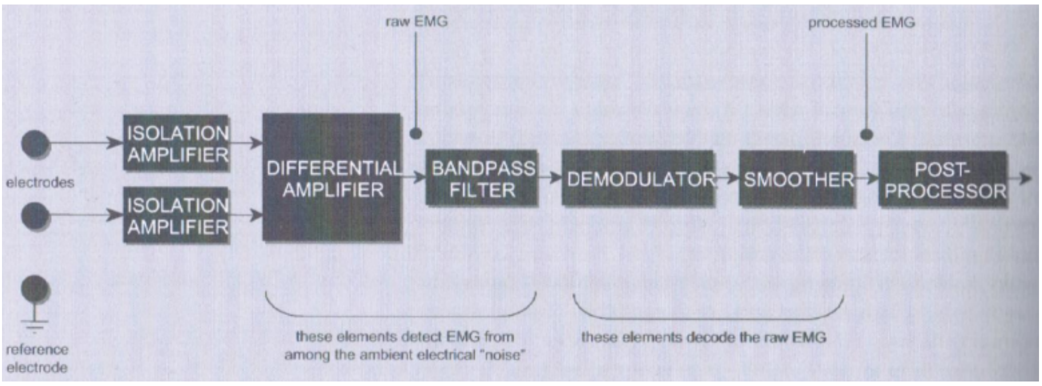

Figure 4: Control scheme of myoelectric prostheses (extracted from [12])

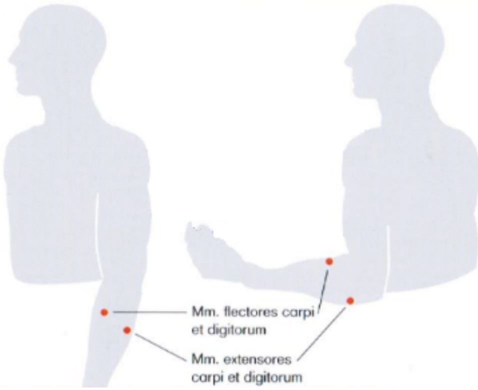

Figure 5: Antagonistic muscles, which are used as transradial myoelectric control source (adapted from [36])

digital control (see Section 3.1.1) was applied. This control method finally got replaced by proportional control (see Section 3.1.2) [37].

3.1.1. Digital Control

Digital control can be described as on-off-control. A myoelectric signal surpassing a threshold causes the electric motor to be actuated and to initiate a prehension movement (hand opening or hand closing). The function as well as the velocity of prehension is predefined [29, 37]. If no sufficiently strong signal is provided to surpass the threshold, the prosthesis keeps in its current status (opened or closed). The opposite prehension movement is accomplished by applying a sufficiently strong signal to the other electrode [13].

Attempts have been made to control both directions of prehension with one electrode. This is called *single-sited* control. One way to implement single-sited control is to execute one function, when a myoelectric signal is applied. The reversed function will be realized, if the myoelectric signal is missing. Another way of realizing single-sided control can be acomplished by defining two thresholds. When the myoelectric signal surpasses the first threshold one function (e.g. hand opening) is enforced. However, if the signal is strong enough to surpass the second threshold, the reversed motion (hand closing) is conducted [12].
The idea of single-sited control can be used to implement additional hand movements (see Section 5.1).

3.1.2. Proportional control

In proportional control there exist a correlation between signal intensity and actuation velocity. The stronger the myoelectric impulse, the faster and/or intensive is the prehensor movement [12, 13, 23, 29, 37]. Thus, the amputee is capable to control the motion of prehension more distinctly.

3.2. Body-powered prostheses

In body-powered prostheses the body movements of the residual limbs or the contralateral shoulder are transformed into prehension motion [3, 37]. In the current, most commonly marketed body-powered prosthesis body movements and the TD are coupled by means of an operating Bowden cable. By creating a relative motion between the attachments of the control cable tension within the cable arises. Consequently, a tensile force is acting on the prehensor causing it to open or close [2]. Since cables can only transmit tensile forces, solely one way of the prehension movement can be actively controlled in body-powered prostheses. The reversed motion takes place passively by means of return elements such as springs or rubber bands [2, 7, 14, 38]. Depending on which prehension motion can be controlled actively, the prosthesis is referred to as "*voluntary-opening*" (VO) or as "*voluntary-closing*" (VC). An amputee using a VO-prosthesis can actively control how much the terminal device will be opened by means of the body motion. Relaxation leads to the terminal device closing by means of a passive element. With VC-prosthesis the closing and thus the gripping force can be controlled precisely. When the body movement is stopped, the TD returns to its default state with its maximal opening width [2, 4, 7, 38–40].

Body-powered prostheses can be further divided into: harness controlled (Section 3.2.1), elbow controlled (Section 3.2.2), rotational controlled (Section 3.2.3) and stump rolling controlled (Section 3.2.4). These different types of control mechanisms and the corresponding body-movements for actuation will be described in the following.

3.2.1. Harness Controlled

For currently, commercially available body-powered prostheses the amputee wears a harness, to which the operating cable is attached to. There exist a big variety of harness designs, which implies different body movements as control input. However, humeral abduction, humeral anteflexion as well as ipsilateral or contralateral shoulder protraction are typically used to tension the Bowden cable and thus operate the prostheses [3, 12, 36].

Generally, the harness system should be chosen depending on the patient's anatomy and physical condition. The harness most commonly used for transradial amputees is the *Figure-of-9*-harness (Figure 6) [12, 41].

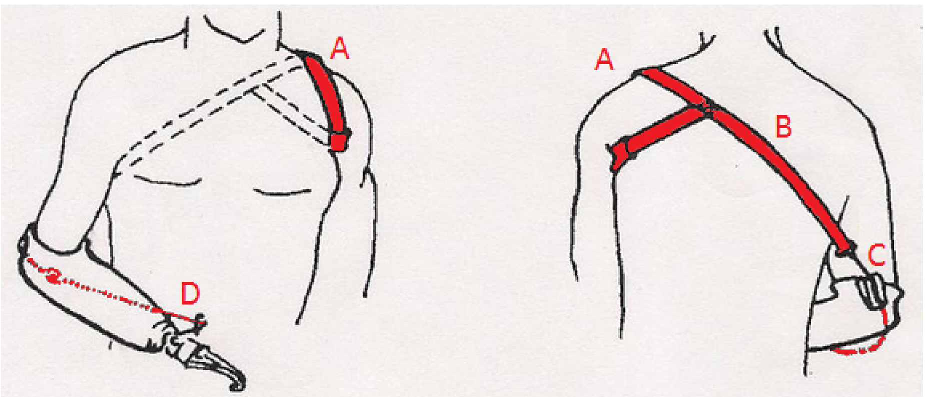

Figure 6: Figure-of-9-harness (adapted from [41])

Compared to other harness designs, this type is very simple. Solely one harness loop **A** is worn around the shoulder of the amputation contralateral side. The strap **B** crosses the back to the ipsilateral side, where the Bowden cable **C** begins and stretches to the terminal device **D**.

The simple strap configuration of the *Figure of 9*-harness is generally sufficient for current body-powered transradial prostheses since nowadays the harness is solely used for prehensor operation [12]. The initially additional function of prosthesis suspension is in the meanwhile accomplished by a self-suspending socket [41].

The harness is often judged by amputees to be uncomfortable or conspicuous. Hence, a lot of research

has been conducted to be able to improve the harness design. D. Latour has introduced the *cutaneous anchor technology*. Instead of the amputee wearing a harness, a mounting plate is simply taped on the scapula of the amputee's affected limb. To this cutaneous anchoring the operating cable is attached to. From there the cable is fixed to prosthetic socket as can be seen in Figure 7.
The anchoring tape is said to stay attached for several days [42].
The amputee controls prehension by movements of the ipsilateral shoulder [42–45].

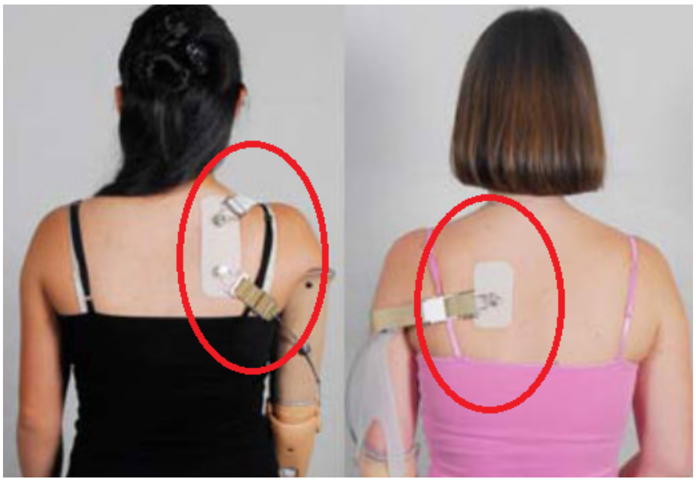

Figure 7: Illustration of cutaneous anchor technology (adapted from [42])

3.2.2. Elbow Controlled

In older literature the flexion- and extension-movement of the elbow is often stated as the control mechanism for the below-elbow prosthesis. The *Below-elbow prosthesis of Charrière*, the *Hand of Dalisch* [6], the *Elbow controlled hand of Leiter* [7], the *Arm of Mietens*, the *Arm of Lange*, the *Troschinski-Arm*, the *Hand of Härtel*, the *Arm of Roeser*, the *Arm of Kuhlmann and Richter* or the *Arm of Jaks* are a few examples of prosthetic devices, in which prehension is powered by elbow movements [12, 46].
The *Arm of Jaks* is illustrated in Figure 8 and its function will be presented exemplarily.

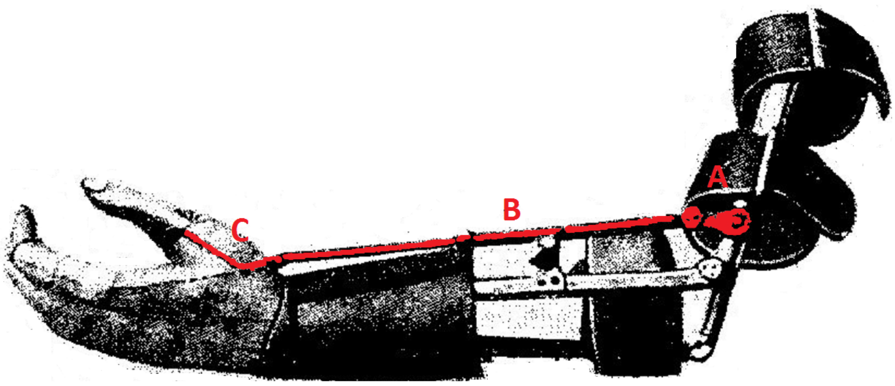

Figure 8: *Arm of Jaks* (adapted from [46])

[6]Multiple prosthetic devices developed by Dalisch are described in Löffer's "*Der Ersatz für die oberen Extremität*". However, the prostheses with rigid connectors and elbow actuation is referred to as *Hand of Dalisch*. The author distinguishes it from the rotational controlled prostheses by calling the latter one *Arm of Dalisch*

[7]In Löffer's "*Der Ersatz für die oberen Extremität*" two prosthetic devices with different control principles are named *Hand of Leiter*. One device is controlled by the elbow and the other one by rotational movement of the stump. Thus, this author talks about the "*Elbow controlled hand of Leiter*" and the "*Rotational controlled hand of Leiter*".

The *Arm of Jaks* consist of an upper arm and a forearm socket, which are rigidly connected. The rigid system comprises a hinge joint at the amputee's elbow. Above the elbow joint a hinge **A** is positioned, to which the rod **B** is coupled. At its distal part rod **B** is linked to rod **C** controlling movement of the thumb. Consequently, when the amputee flexes his/her arm, rod **B** is dragged in proximal direction. Thereby, the thumb is rotated counterclockwise causing hand closing. On the contrary, elbow extension leads to hand opening [46].
Former graduate students of Stanford University, nowadays part of th *WILMER* reasearch group at TU Delft picked up this control principle for their design shown in Figure 9 [12, 47].

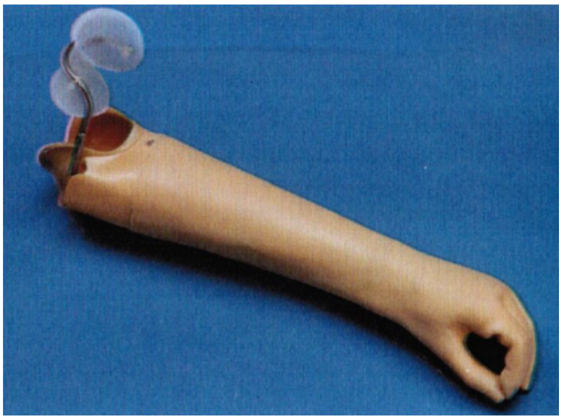

Figure 9: *WILMER elbow-control* (extracted from [12])

For the *WILMER elbow-control* a control shell is placed on the upper arm of the amputee. A hinge spanning the elbow joint connects the control shell to the prosthetic socket and additionally interferes with the control cable. Extending the elbow leads to tension in the control cable and thus terminal device opening. A spring element returns the prehensor into its closed default state as soon as the elbow is flexed again [12].
The open-source e-NABLE Community for 3D-printed prosthetic devices also applies this control method to their *Unlimbited Arm* and *RIT Arm* [48].

3.2.3. Rotational Controlled

Depending on the length of the stump of the amputee, forearm rotation can partially be restored [49]. In Figure 10 the correlation between stump length and possible range of rotational motion is illustrated.

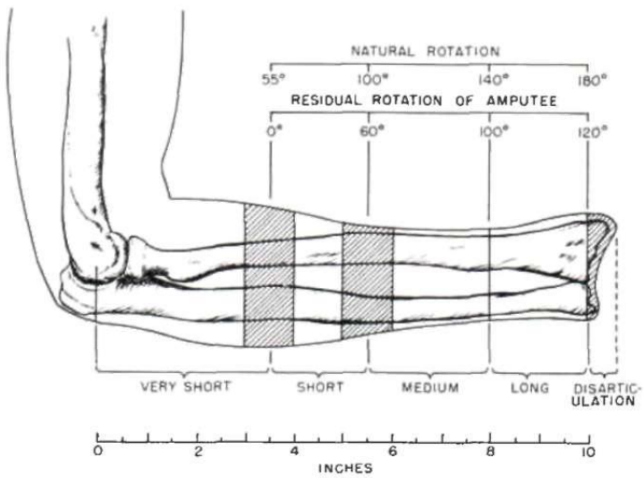

Figure 10: Remaining stump rotation (extracted from [50])

When an amputee has a stump length of about 5 inches (approximately 12,7 cm) or longer, some stump rotation remains and can be coupled to prosthetic prehension. The first device known with this rotation control was developed by Dalisch from Neiße in 1857 [46]. As shown in Figure 11 his design comprises two shells, which are connected by a hinge joint. One shell **A** embraces the upper arm tightly. The other one **C** wraps around the forearm in such a way that pronation and supination of the forearm can still be conducted. In the opening **b** the capsula **D** is inserted. The capsula **D** envelops the distal part of the stump in such a way, that rotational movement of the stump is transferred into rotational movement of the capsula **D**. At the front of the capsula **D** a "quick-screw", a screw with a very steep thread, is attached. The screw inserts in a nut, which is linked to the finger control plate **m**. From this plate five metal rods **2** originate. Each rod **2** leads to a pulley **3**, which represents a metacarpophalangeal joint. The proximal and distal interphalangeal joints are constructed in a similar way: as pulleys **7** and **9**, which are connected by rods **5** and **10** [46]. Hence, pronational movement of the stump and consequently the screw is transformed into displacements of the control plate **m** along the longitudinal axis of the forearm. The finger rods are pulled in proximal direction, causing the pulleys to rotate counterclockwise and leading to finger flexion [46].

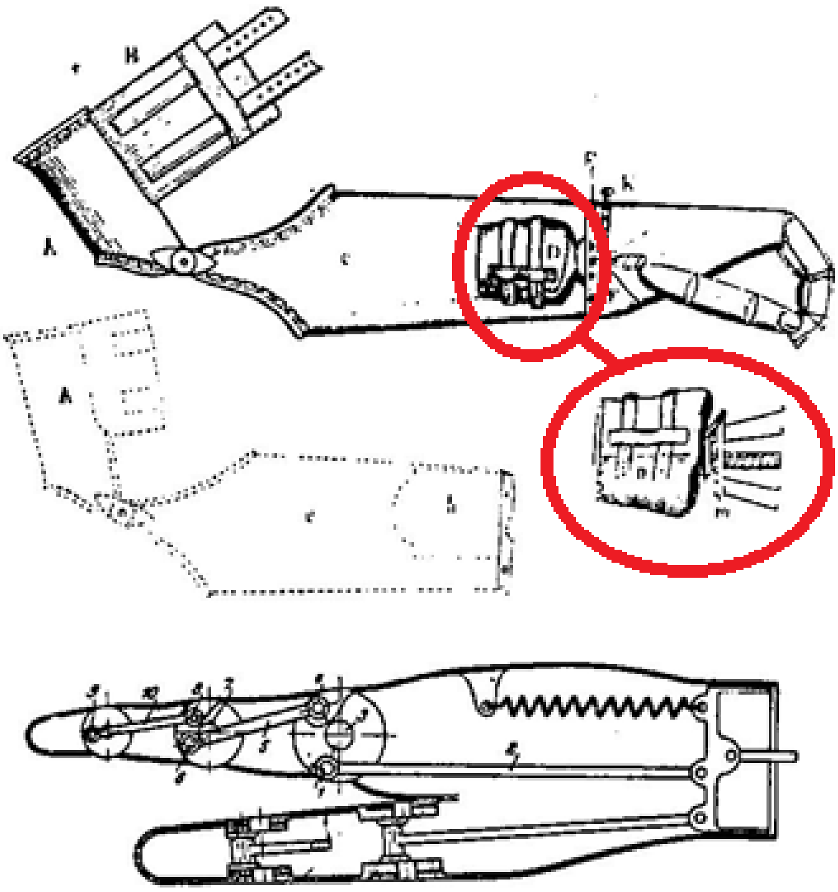

Figure 11: *Arm of Dalisch* (adapted from [46])

Rotational prehension control is also applied in e.g. the *Hand of Georg Härtel*, the *Rotational controlled Hand of Leiter*, the *Arm of Erlacher*, the *Zawodnik Hand* or the *Rohrmann Hand with pronation actuation* [46, 51].

3.2.4. Stump rolling controlled

Sauerbruch has designed a hand, which is controlled by rolling movement of the stump. The prosthetic hand is illustrated in Figure 12. The amputee rolls his/her stump over the plate **c**. Owing to the tilting movement of the plate **c**, the cable **f** is pulled and opens the hand. A spring brings the hand back into a closed position as soon as the cable tension is released.

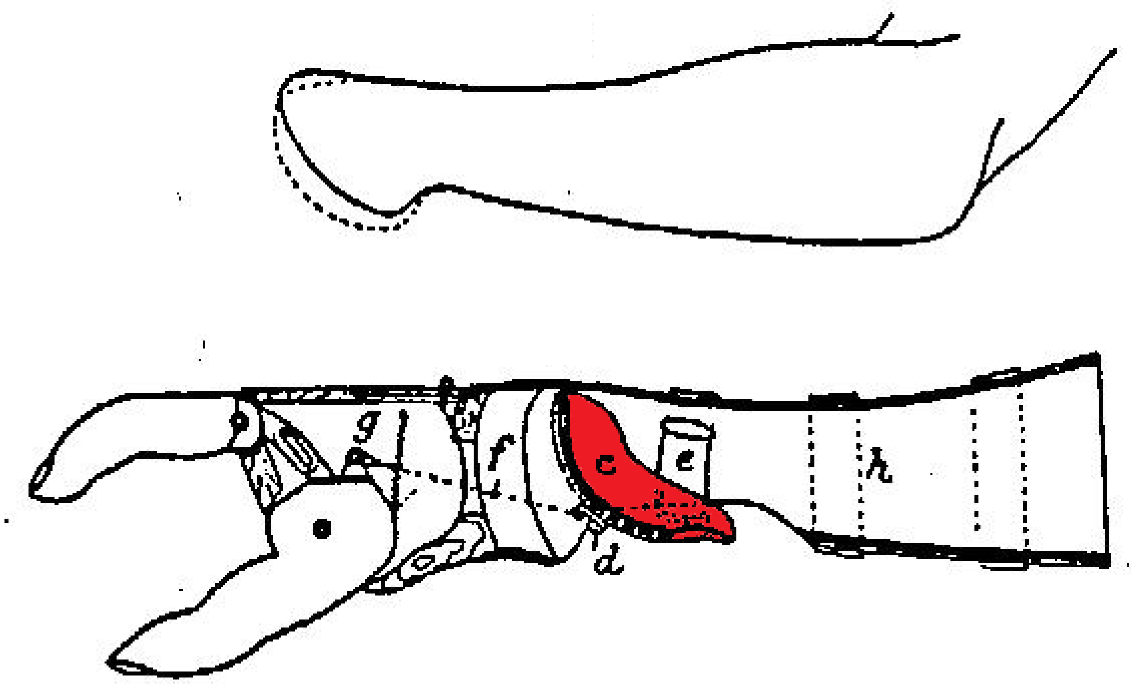

Figure 12: *Hand of Sauerbruch* (adapted from [46])

4. Changing grasp modi

Various different grasp types can be conducted with the human hand. The grip patterns are distinguished depending on the number of fingers involved (e.g. power grasp versus pinch grasp) or with regarding to the thumb position (e.g. lateral versus opposed pinch). In this chapter, it will be studied how different grasp patterns are achieved in prosthetic hands. Consequently, it will be examined how the fingers can be flexed independently and how it is realized that the thumb can be switched between reposition and opposition. First, it will be shown how it is accomplished in myoelectric hands. There a special focus will be put on the most advanced commercially available ones. Following this, attempts of body-powered prostheses will be presented.

4.1. Myoelectric prostheses

A big variety of myoelectric prosthesis designs, which are capable to alter the grasping mode, can be found in literature. Thus, it would go beyond the scope of this report to describe the characteristics of each control mechanism in detail. However, a few similarities of the various number of designs can be pointed out. For example in almost each design a defined trigger signal (impulse) or a signal sequence (double impulse, co-contraction [8]) can be used to alter between grip patterns [52]. Sometimes a button or a switch is implemented to activate additional grasp types [52].
The myoelectric prostheses commonly have multiple actuators to move the fingers and possibly the thumb. In the following it will be zoomed in on the most advanced commercially available myoelectric prostheses (Michelangelo, i-Limb Quantum, BeBionic v3, VINCENTevolution2). Their control methods

[8]Co-contraction is the simultaneous tensioning of antagonist muscles. In the forearm, co-contraction can be achieved by e.g. clenching the hand to a fist or extemding all fingers simultanously.

will be depicted in more detail.

4.1.1. Michelangelo Hand

The *Michelangelo Hand* developed by *Otto Bock HealthCare Products GmbH* in Vienna was the first commercially available multiarticulating hand with a myoelectric thumb reposition/opposition control. The hand comprises two actuators, which are controlled by two electrodes. One actuator drives the flexion/extension of the thumb, index finger and middle finger actively. The fourth and the little finger are solely passively dragged along. The second actuator alternates the thumb between its lateral and opposed position [53, 54].

The hand is able to perform seven different grasp patterns. To switch into the desired one, the amputee first has to select the appropriate thumb mode (lateral or opposition mode) by giving a trigger signal. A trigger signal can be e.g. an impulse from either the electrode recording the "*opening*"- or the "*closing*"-signal, co-contraction or a prolonged "*opening*"-signal. Having given the trigger signal, the thumb will follow its new motion path when the next "*closing*"-signal is given [55].

Depending on the activated thumb mode different grip types can be accomplished by varying the hand opening width. When having selected the opposed position of the thumb, a narrow grip width leads to a *tripod pinch* to securely hold small objects. In contrast to this, keeping a big grip width results into a *opposition power grip*. When the *open palm*-grip is desired, the amputee needs to switch into the opposition mode of the thumb, but at the same time he is required to apply an opposing force to the thumb movement. The opposing force can be caused by pushing against the thumb with the sound hand or an assistive object like a table. Thus, the thumb will be directed into a wide-opened palmar position.

It is possible to activate a physiologically neutral hand position as rest position of the prosthesis. The hand will move into this position, if no muscle activity has occurred after a predefined period of time.

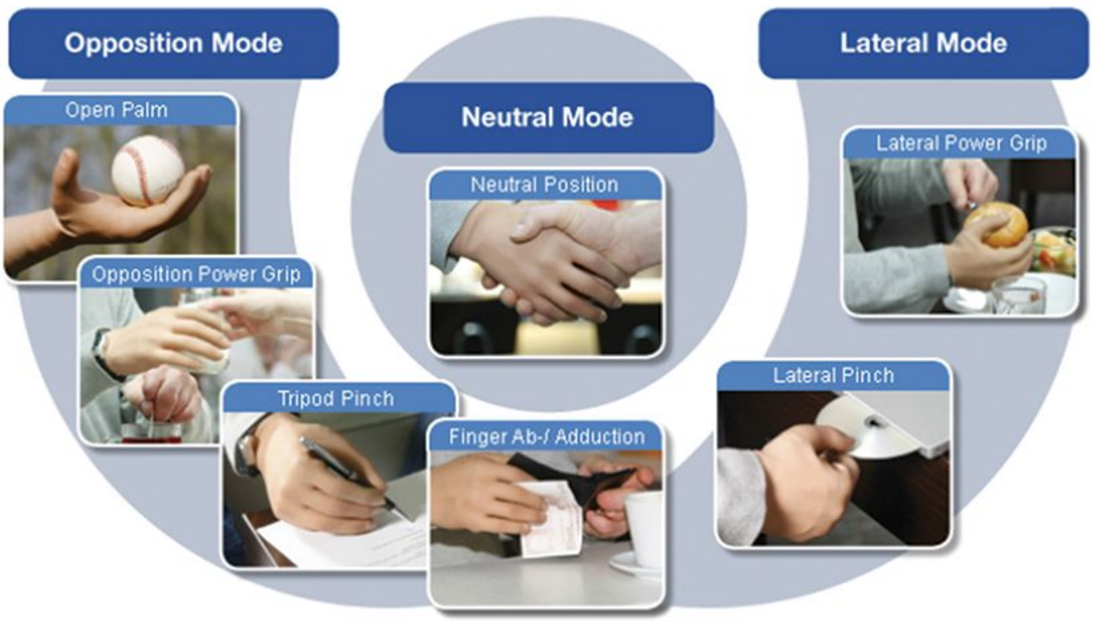

Figure 13: Grip patterns of the Michelangelo Hand and corresponding thumb position (extracted from[56])

4.1.2. i-limb^{TM} quantum

The *i-limb^{TM} quantum* hand is the newest development of *Touch Bionics Inc.* in Livingston. Five actuators drive independently flexion/extension of the four fingers and the thumb. A sixth actuator is responsible to move the thumb from opposition to reposition [18, 53].

The *i-limb*^{TM} *quantum* facilitates 24 standard grip patterns and additional 12 grips can be programmed based on the users wishes. Up to two surface electrodes are used to record myoelectric signals. Prosthetic prehension is accomplished proportionally to these signals. Additionally, predefined trigger signals can be used to initiate grip pattern alteration. When having the hand in the fully opend position, the trigger signal can be applied to cause the hand to change the grasp type. The trigger signals can be e.g. two impulses, three impulses, co-contraction or a pre-longed opening signal [18].

In addition to the EMG signals, *Touch Bionics Inc.* supplies three other methods, the amputee can use to control the numerous grip patterns (see Figure 14): gesture control with the *i-mo*^{TM} *technology*, the *quick grips*^{TM}-app or by approaching a *grip chip* ^{TM} [18, 57, 58].

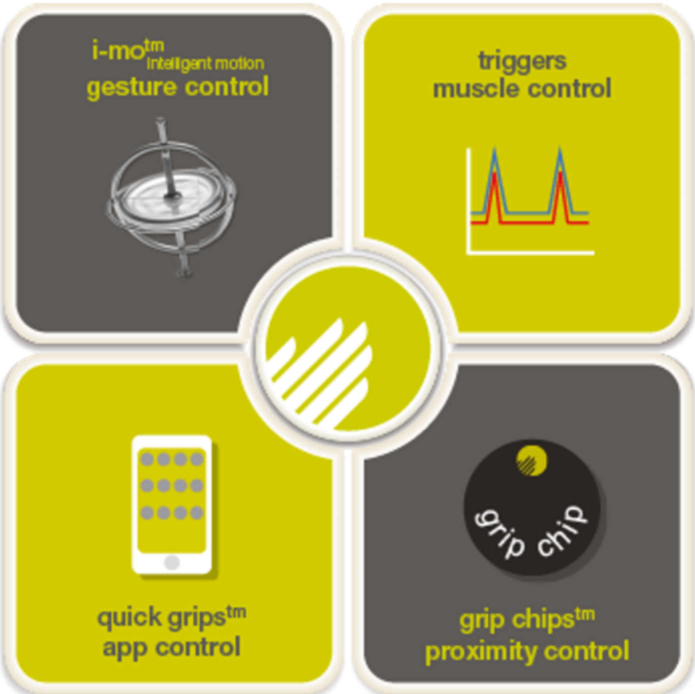

Figure 14: Mechanisms to alter grip patterns of i-limb^{TM} quantum (extracted from[18])

Four additional grip patterns can be controlled by means of the newly developed gesture control *i-mo*^{TM} *technology*. For this, the elbow has to be flexed 90° orienting the forearm parallel to the ground. The starting point for the gesture control is the natural hand position. When having the hand in this position the amputee needs to give an open signal to activate the gesture control. As soon as the index finger twitches, illustrating the gesture control being activated, the amputee must move the hand instantaneously in anterior, posterior, medial or lateral direction. The prosthetic hand will switch into the grasp type, which has been predefined to the direction of the just applied movement [18, 57, 58]. With the *quick grips*^{TM}-app installed on a smart-phone or tablet, the user can selected the desired grip pattern by simply selecting the corresponding icon [18, 58].
The forth method to alter grasp patterns can be conducted by means of the bluetooth chips, called *grip chips*^{TM}. A particular grasp pattern is assigned to the chip. If the amputee has set the hand into normal position, he can activate the gripping mode programmed on the chip by simply approaching it. Grasp switching is initiated, if the hand is within a radius of 6 inches (approx. 15 cm) away from the chip. The chip can be attached to different objects and the grasp type required to handle the object or needed in the environment can be programmed [18, 58].

4.1.3. BeBionic v3

RSL Steeper in West Yorkshire has already launched its third generation of the *BeBionic hand*. Each finger and the thumb comprise an individual motor. Hence, in total fourteen different grip patterns can be formed [16, 53]. However, due to the underlying grip selection strategy of the prosthesis, not all fourteen grip patterns are available at all times. The amputee can select up to eight grip patterns, which will be preset to its device.
The first indicator to select a specific grip pattern is the position of the thumb. By moving the thumb passively with the sound hand it can either be set into the "*opposed*" or in the '*lateral*" position. In each thumb position, there exist a primary and a secondary mode, between which can be alternated by pressing the program switch button on the dorsal side of the prosthetic hand for less than 2 seconds [59]. In each mode, there is a default grip pattern mode as well as an alternative mode programmed. In order to switch between these mode types, the patient must first open the hand completely, remove the signal and finally apply an additional "*opening*" signal [59]. Figure 15 shows exemplarily possible switching sequences.

Figure 15: Flow diagram for grip pattern selection of the *BeBionic v3*

In the following the switching sequence to achieve the "*Mouse*" grip pattern will be delineated. First of all the thumb needs to be moved to its "*lateral*" position. Estimating the primary mode being activated in the device, the user needs to press the program switch button shortly. After the hand having moved into the "*Column*" grip pattern, which would be the default state, the amputee needs to open the hand completely and finally give an additional "*opening*" signal. By this the prosthesis is switched into the alternative mode as which the "*Mouse*" grip pattern was programmed.

4.1.4. VINCENTevolution2

VINCENTevolution2 is the updated multiarticulated hand prosthesis of *Vincent Systems GmbH* in Karlsruhe. The prosthesis comprises six motors actuating each finger individually and the thumb [52, 53]. The user is able to switch between 12 different grip patterns easily by two electrodes sensoring EMG signals. The underlying control concept is named "*Single Trigger Control*". At this, a particular grip pattern is selected depending on the one, the hand is currently in [60]. The switching is mostly conducted by a predefined trigger signal, which can be e.g. a peek signal or co-contraction. For the grip choice a default state is defined, which serves as a reference state. From here an "*opening*" as well as a "*closing*" signal, the trigger signal or the absence of a signal, can alter the grasping type as well. The change of grip pattern is defined by a flow diagram, which the amputee needs to memorize and follow [52]. An example of such a flow diagram is illustrated in Figure 16.

Figure 16: Exemplary flow diagram for grip pattern selection (extracted from [52])

In this example, the *open palm*-grip is defined as the default state. This is a neutral state, from which other grasp types can be obtained by a specific control signal. Having the prosthesis in its neutral state a "*closing*" signal activates the finger joints, which will be flexed for a lateral grip. An additional "*closing*" signal will initiate the lateral grip proportional to the signal strength.
An "*opening*" signal applied with the prosthesis currently being in its default state will lead to an *index point*. Next, a flexion of the index finger can be obtained by an additional "*closing*" signal.
When applying the trigger signal with the hand in the default state, the joints of the index finger will be activated. Consequently, a following "*closing*" signal will flex the index finger while keeping the remaining fingers extended.
If the hand is in the default state and no signal is given within a predefined time period, the hand will move into physiologically neutral hand position. From there, a power grip will be initiated when a "*closing*" signal is applied.
From each of these directly selected grip patterns, a second control level with new grasps can be selected by means of the trigger signal. In each grasp type, the opening width of the fingers can be controlled proportionally from fully opened to fully closed.
No matter which gripping mode is active, the hand is reset to the default state employing a long "*open*"-signal [52].

4.2. Body-powered prostheses

In the prior subsection it was presented how multiple grasp types are successfully realized and controlled in myoelectric prostheses. In the following, attempts of body-powered prostheses facilitating different grasp patterns will be described. First general attempts will be depicted followed by VO/VC-devices, which can be actively controlled throughout the whole prehension cycle.

4.2.1. Multigrasp prostheses

In early records attempts to design active prosthesis with multiple grip patterns and an opposable thumb were already described. In 1818 for example Peter Ballif tried to develop a hand prosthesis (see Figure 17) with two different control mechanisms: one string controlling the extension of all fingers and one string for individual thumb movement [12, 51].

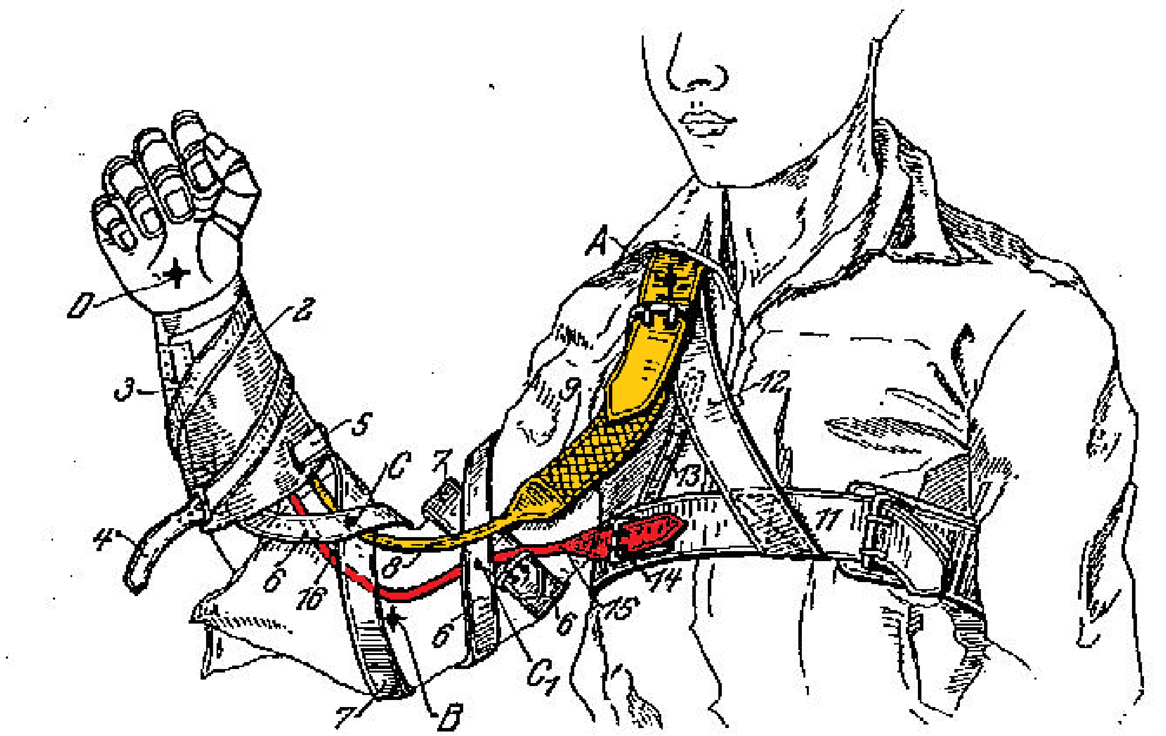

Figure 17: *Hand of Ballif* (adapted from [51])

The amputee wears a harness to suspend and control the prosthetic device. The harness comprises two different control strings. The first control cable (marked red in Figure 17) is attached in point **14** to the waist belt of the harness. It continues as the string marked as **15**-**16** and is attached to the primary slider, which drives the extension of the four fingers and the thumb simultaneously (see Figure 18). By abducting the upper arm, the cable **14**-**15**-**16** is tensioned causing the four fingers and the thumb to extend.
The supposed thumb control string originates in the pit of the collarbone **A**. It continues as the elastic strap **9** and the inelastic strap **8**. According to Ballif's explanation of the prosthetic mechanics extending the elbow leads to independent thumb movement. However, in Figure 18 Ballif's drawing of the prosthetic palm is shown. It can be seen that Ballif's drawing and the verbal description of the prosthesis do not correspond. Instead of the thumb control cable being directly attached to the thumb, it is combined with the second control cable and finally attached to the primary finger slider. Consequently, no independent thumb movement is possible. In contrast, elbow extension would lead to the extension of all fingers including the thumb [51].

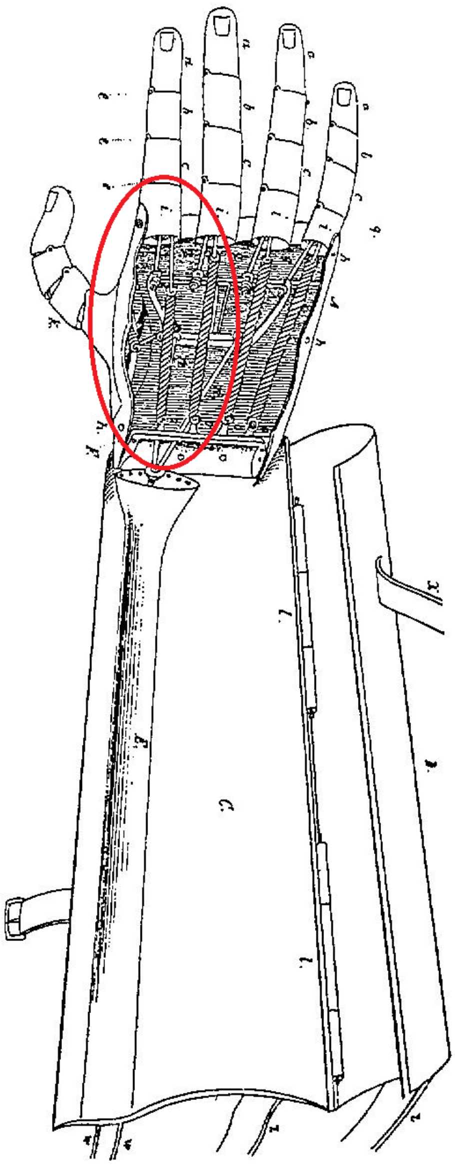

Figure 18: Inside of *Hand of Ballif* (extracted from[46])

At least, Ballif achieved a time shifted thumb movement by having its attachment to the primary slider more tightened. Hence, the thumb extends earlier than the remaining fingers when a control cable is tensioned [46]. Flexion movements are conducted passively by means of tension springs [46] with the thumb being delayed.

Karoline Eichler succeeded to construct her prosthetic design in such a way, that it enables different grip patterns. The mechanisms of her design is illustrated in Figure 19.

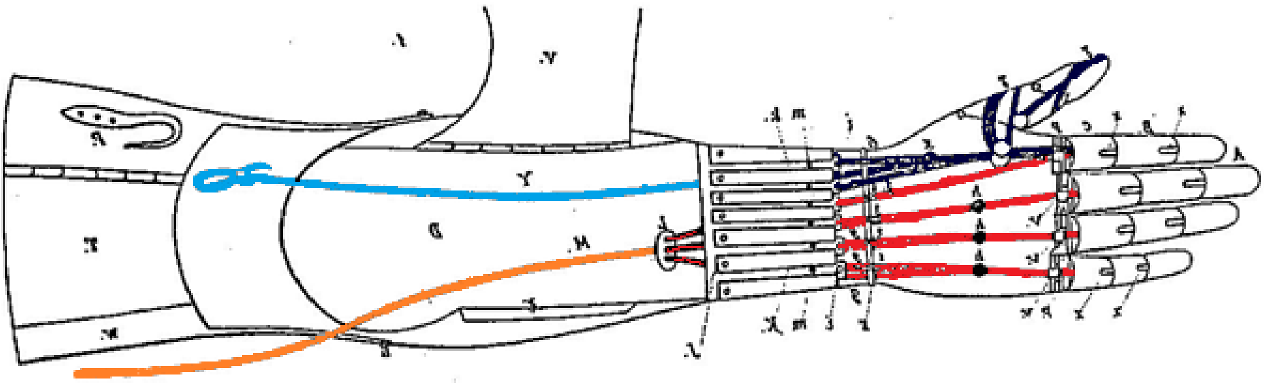

Figure 19: *Hand of Eichler* (adapted from [46])

The hand consist of four groups of strings: two primary and two secondary strings. The primary strings are directly connected to the fingers. The secondary strings intervene with the primary strings and serve as control cables.
One primary string (marked red in Figure 19) reaches along each individual finger. The other primary string (marked dark blue in Figure 19) comprises solely the index finger and the thumb. Consequently, the latter primary string is responsible for the index finger and the thumb bending separately from the other fingers.
The secondary string **Y**(marked light blue in Figure 19) interfering the latter described is attached to the anterior side of the upper arm socket. Extending the elbow causes the index finger and thumb to approach resulting in a pinch grip [46].
The other secondary string **M** (marked orange in Figure 19) is connected to both primary strings. This string leaves the upper arm socket and is fixed on the chest. Therefore, abduction of the forearm causes all four fingers and the thumb to close leading to a power grip [46].
Spiral springs (β and γ) on each finger joints cause the extension of the fingers after tension force is released [46].

These just described devices are some of the earliest stated attempts for multigrasp prostheses. However, multiple other engineers have also worked on other designs. The various attempts can be categorized as devices with additional control cables requiring the sound hand, having a particular closing trajectory, having a distinct thumb alignment, having default and secondary grasps or as applying the principle of underactuation. The mechanism of at least one device of each category will be explained in the following.

Using additional control cables

Apart from K. Eichler G.R. Tureman, Jr. for example added additional control cables in order to achieve a body-powered multigrasp prosthesis. The hand prosthesis comprises one cable to manipulate the flexion of the thumb and three additional control cables to operate the other fingers as illustrated in

Figure 20 a).

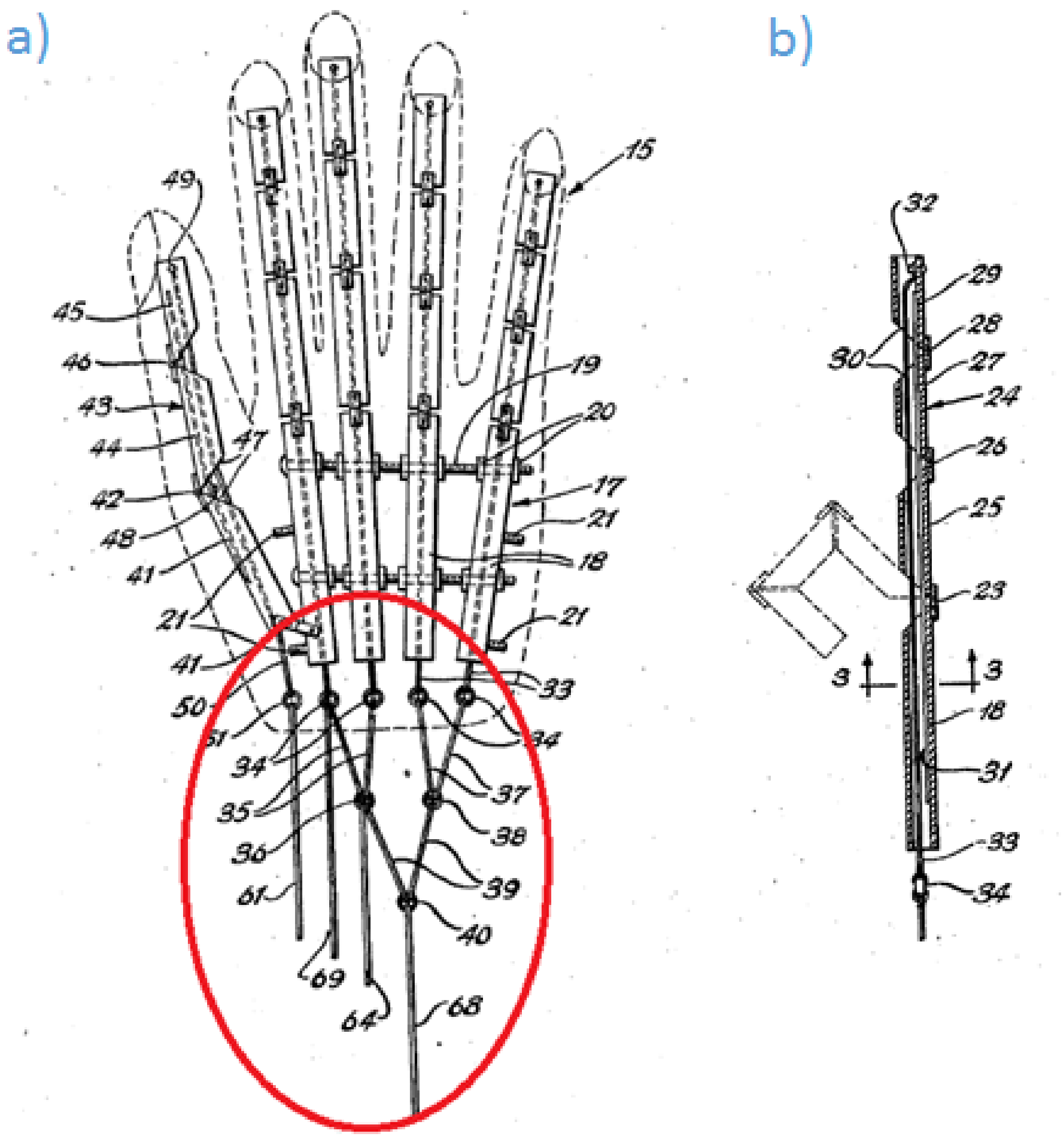

Figure 20: Prosthetic hand with multiple control cables (adapted from [61])

In Figure 20 b) the mechanism of a finger is illustrated. Each finger consist of four tubular segments **29**, **27**, **25** and **18**. Adjacent segments are connected on the dorsal side by the hinge joints **28**, **26** and **23**, which represents the finger joints. On the palmar side of the fingers the material across the hinge joints is cut away to ensure joint movability.

A leaf spring **31** and a string **33** passes through the tubular system from their finger attachment point **32** towards the palm unit **17**. The leaf spring is fixed to the last tubular segment **18** and tends to keep the fingers in an extended position. The string **33** continues into the palm unit **17**, where it is attached to the dee **34**.

To dee **34** of the index finger, there is the individual control cable **69** attached to as well. Furthermore, the dee **34** of the index finger and the dee **34** of the middle finger are coupled by the strings **35** united in the dee **36**. The individual control cable **64** is also fastened to dee **36**.

The strings **37** combine the ring and the index finger in the dee **38**. The dees **36** and **39** are again

connected by strings **39** in dee **40**, which also has the control cable **68** tied to it.
The mechanism of the thumb is comparable to the finger structure. However, the thumb solely has two hinge joints **46** and **42**. Its string **50** changes at dee **51** into the individual control cable **61**.
Consequently, there exist four different cables, each controlling different fingers or finger combinations:

- Control cable **61** is responsible for the thumb movement.
- Control cable **69** influences solely the index finger
- Control cable **64** manipulates index and middle finger
- Control cable **68** operates all fingers simultaneously.

Depending on which control cable is manipulated, different grasp types can be achieved. The high number of control cable require a special harness design, which is shown in Figure 21.

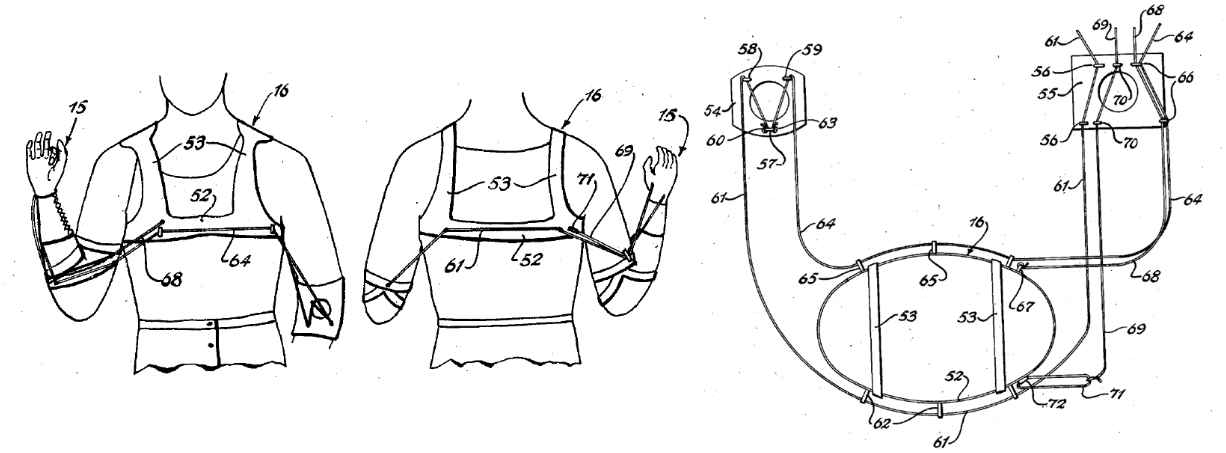

Figure 21: Prosthetic hand with multiple control cables (extracted from [61])

In the harness illustrated, the thumb control cable **61** is is guided along the amputees back and attached to the cuff **54** on the contralateral elbow joint. Control cable **64**, responsible for index and middle finger, is also attached to this cuff, but is directed anterior along the chest. Consequently, both cables can be manipulated simultaneously by flexing the elbow of the sound arm. However, by protracting the contralateral shoulder, cable **61** can get tensioned independently from cable **64**. The index finger control cable **69** is attached on the ipsilateral shoulder **72** and hence, can be operated by ipsilateral elbow flexion. Cable **68** is fixed at **67** on the chest, so that all fingers are flexed, when the amputee abduct his arm.

Requiring sound hand

The characteristic of an opposable thumb is implemented e.g. in the *Troschinski-Arm*. Here the thumb can be alternated between a lateral, a slightly opposed and an extreme opposed position by means of the sound hand [46].
C.D.W. Blatchford and W.A.D. Blatchford have also patented a thumb, which can be changed between lateral and opposed position [62] as shown in Figure 22. When the thumb is rotated by means of the sound hand, a pin **8** attached to the bottom of the thumb portion **5** is moving within slot **12** in the hand portion **1**. Hence, the rotational movement is restricted to this circular segment. The two recesses in the thumb part are required for locking the thumb in its lateral or opposed position. A spring **14** located in the hand part presses a ball **13** into one of the recess preventing involuntary rotational movement of the thumb.

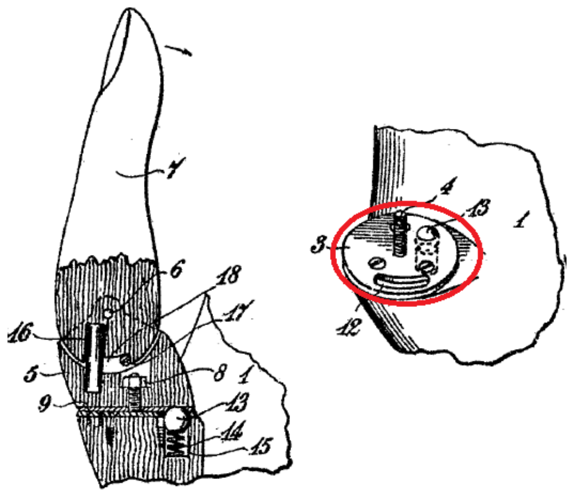

Figure 22: *Thumb of Blatchford* (extracted from [62])

The *Northrop Aircraf, INC.* has also developed and patented hand prostheses with the possibility to move the thumb between opposition or reposition by means of the sound hand or by striking it against an assistive object [63–65].
In the *Northtrop Hand Model No. 2* (Figure 23) the flexion movement of the thumb is coupled to the flexion movement of the remaining fingers. When the amputee tensions the control cable, it drags the connector **30** and the coupled rack **91** along in proximal direction. This leads to a counterclockwise rotation of lever **104**, which is attached to rack **91**. Since the rod **113** is linked to lever **104**, its rotation causes the rod **113** being pushed in distal direction. This in turn initiates a clockwise rotation of the attached linkages and the mounted gear **146**. Latter intervenes into ratchet **150** and drives the thumb to close. With the sound hand the amputee can rotate the thumb around the axes **126** and thus, switch the thumb being opposed or lateral positioned with respect to the remaining fingers. The thumb is prevented from moving involuntarily by means of the frictional member **136** [63, 65].

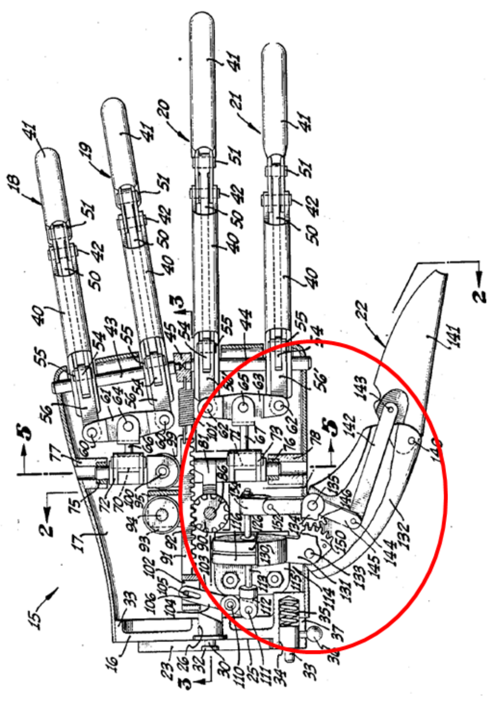

Figure 23: *Northtrop Hand Model No. 2* (adapted from [63])

The flexion movement of the thumb is implemented in the *Northtrop Hand Model No. 3* (Figure 24) by means of a bevel and worm gear. This movement also goes along with flexion of the remaining fingers. When the control cable is manipulated, the shaft **79** and the attached bevel gear **83** are rotated. The latter drives the bevel gear **160**, which is connected to the worm **161** and hence, drags it to rotate along. Since the gear **161** intervenes with the gear **162** at the proximal thumb part, its movement causes the thumb to flex. Rotation of the parts in the opposite direction, will cause the thumb to extend again. The thumb can be moved passively into a lateral **A**, a middle **B** and an opposed position **C**. Each position is defined by a recess **151**. to lock the thumb in the desired position, the spring **154** presses the pin **150** into the corresponding recess [64, 65].

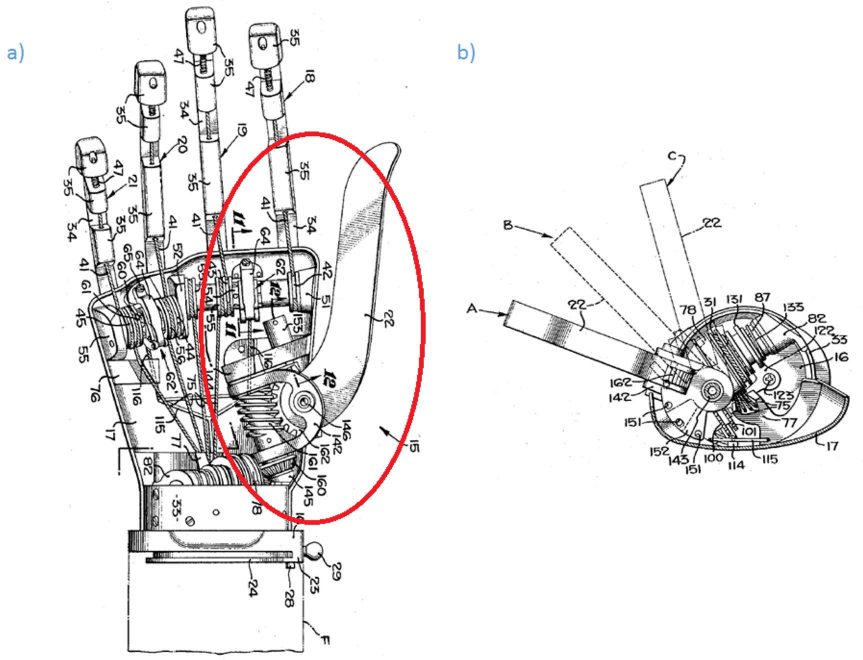

Figure 24: *Northtrop Hand Model No. 3 with a) hand mechanic and b) thumb positions* (adapted from [64])

The *Northtrop Hand Model No. 5* (Figure 25) is a modification of *Northtrop Hand Model No. 2*. The alternation of the lateral or opposed thumb position is comparable. However, in this design flexion of the thumb is conducted passively by manipulating the thumb against an object or the sound hand. When force is exerted on the posterior thumb side, it is rotated in counterclockwise direction. By this, the detent **194** can strike the jut **210** of detent **200** and initiates its clockwise rotation. The leaf spring **203** supports the rotational movement until the lip **196** of detent **200** and the lip **195** of detent **193** are wedged. When the external force on the thumb is released, the detents **200** and **193** will remain interlocked, securing the thumb in the flexed position. When another external force is applied to the back of the thumb, the connection will be released. Then the torsion spring **211** causes the thumb chassis **22a** to rotated in clockwise direction [63, 65].

Grasp types either vary regarding the thumb position or regarding the number of fingers involved. In other devices different grasp types are achieved by having the amputee select, which fingers will follow the control cable action. In the *Arm of Klingert* or in Pfister's second arm this principle is applied. An amputee controls the closing of Pfisters second arm by flexing his/her elbow. Having the fingers flexed the amputee can lock the position of each finger individually. Therefore, he/she moves the slider corresponding to the finger by means of the sound hand [46]. The sliders are positioned on the lower part of the prosthesis as can be seen in Figure 26.

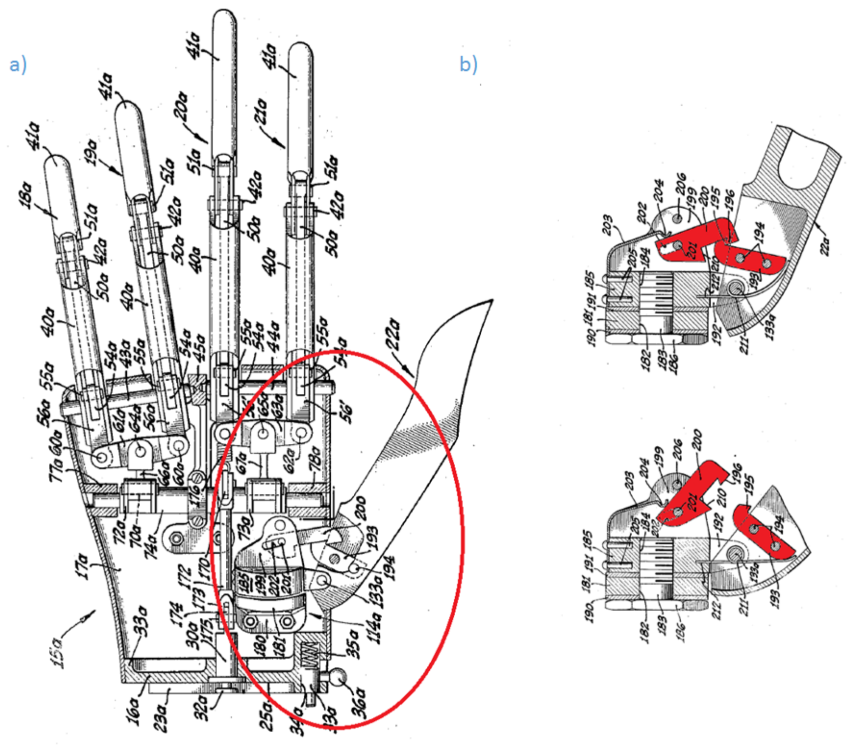

Figure 25: *Northtrop Hand Model No. 5* with a) hand mechanics and b) thumb flexion mechanism (extracted from [63])

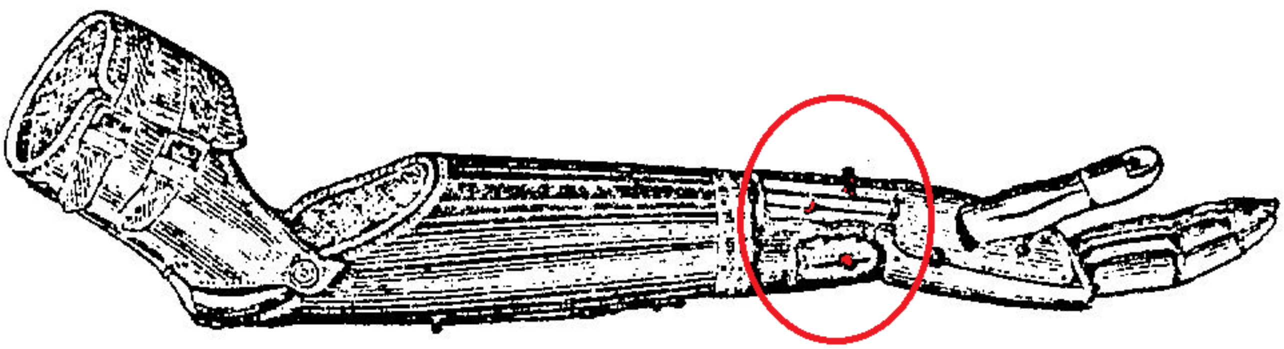

Figure 26: Second arm of Pfister (extracted from [46])

When the amputee relaxes his/her elbow, springs pull the fingers, apart from the locked ones, back into their default state. By alternating which fingers are locked, different grip patterns can be retained. In addition to this, the thumb position can be alternated in three different positions by means of the sound hand. Depending on the selected position the thumb either touches the tip of the index finger or the hand closes to a fist [46].

Define closing trajectory

The device of patent *GB 862,437* (Figure 27) comprises a stationary thumb **b** and two movable fingers **c** and **d**. The fingers follow a special trajectory during hand closing: in addition to moving towards the thumb tip b^1 they also approach each other. Therefore, an object can be grasped between all three fingers with three contact points or clamped between the two movable fingers. The closing trajectory of the fingers are defined by their axes of rotation **f** and **e**.
Finger movements are driven by the worm wheels **h** and **g**, which intervene with the worm screw **k.**

The latter is coupled to a pulley **j** with the control cable **l-m** [66].

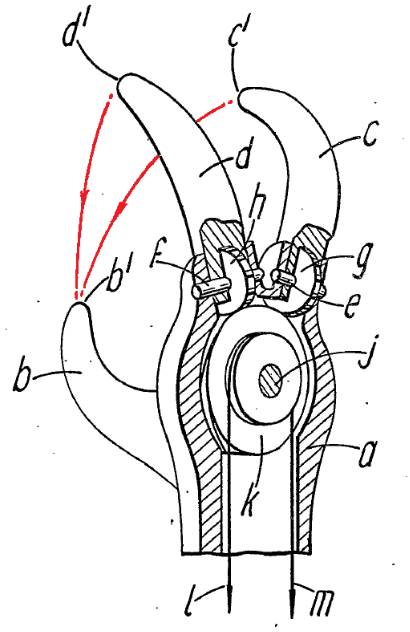

Figure 27: Multigrasp prosthesis due to distinct closing trajectory (extracted from [66])

Distinct thumb alignment

Troendle used a fourth concept to ensure different grasp types. In order to establish a pinch grip for thin objects as well as a power grip for big objects, he positioned the thumb in an angle of 120° to the middle finger as shown in Figure 28 a). By alternating the grip width to the other finger, different grasping types can be accomplished: a pinch grip as shown in Figure 28 b) or a power grip as can be seen in Figure 28 c). The adaptation of the opening/closing width of the thumb are conducted passively. Grip strength is achieved thru the other fingers, which are operated by the amputee lifting the shoulder [46, 51].

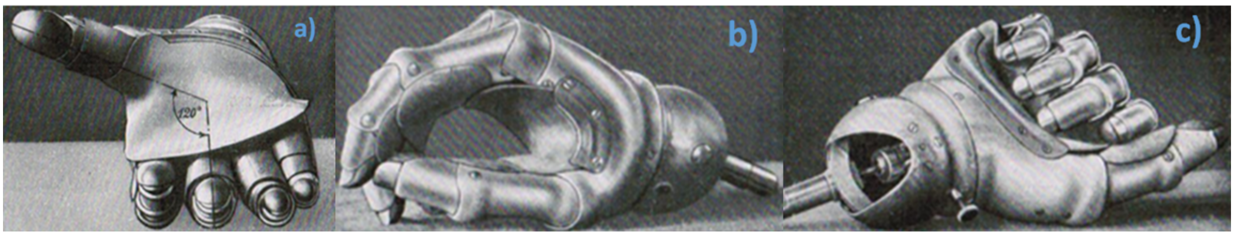

Figure 28: *Hand of Troendle* showing the finger alignment (top), a pinch grip (middle) and a power grip (bottom) (extracted from [51])

Default and secondary hand grasps

With the hand designed by Bethe (Figure 29) the amputee can generally conduct a pinch grip. However, when having an object positioned within the hand palm, the object passively changes the finger grip by pushing against a lever (marked red in Figure 29).

By pulling chain **1** the circular segment **2** is rotated counterclockwise. The lever attached to the circular segment **2** moves the slider **3** in proximal direction against the force of a compression spring. The chain **4** is fixed to slider **3**, which follows its movement and hence, it tensions the spring **9**. Furthermore, chain **4** passes the chain wheels **5**, which are coupled to the shaft **6**.

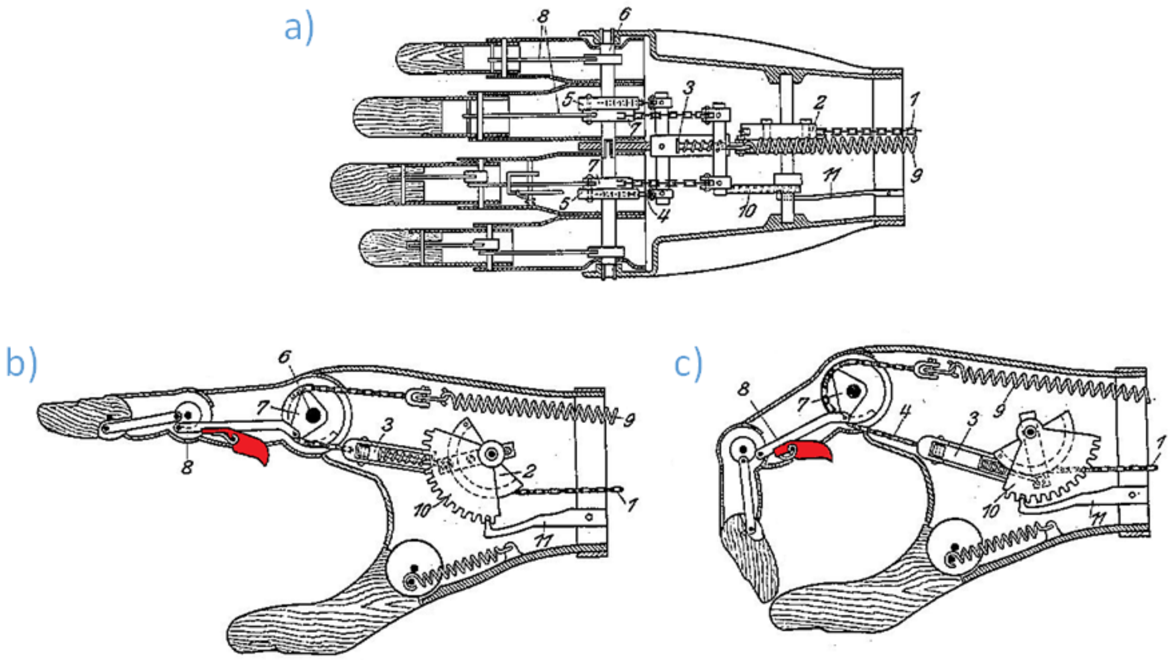

Figure 29: *Hand of Bethe* with a) hand mechanics, b) default pinch grip c)secondary power grip (adapted from [51])

The shaft **6** represents the first joints of each finger. By means of the plate **7** it causes the first finger segment to move. From plate **7** a rod stretches to the second finger segment and is attached to it. The finger segments are coupled by means of a shaft. For the index and middle finger and additional rod stretches to the third finger segment. When chain **4** is moved counterclockwise it drives the chain wheel **5** and the shaft **6** in the same rotational direction. Since the plates **7** follow this movement, the fingers will close conducting a pinch grip.
However, when an object is positioned within the hand palm, it will push against the lever marked red in Figure 29. Therefore, the lever pushes the rod **8** in counterclockwise direction causing the second finger joints to flex further. The finger tips of the index and the middle finger will slide along the thumb palmar side causing it to shift medial. Consequently, a power grip is conducted.
This movement is possible due to the hand being stiff in the direction of the movements of the remaining fingers, but being flexible mounted in the perpendicular direction.

E. Robinson has patented in *GB 116,968* [67] a VC device with the thumb being positioned in lateral configuration as long as no tension is applied to the control cable (see Figure 30). However, depending on the position of toggle **s**, the hand can be closed either to a lateral or to an pinch grasp.

The thumb consist of three parts, which are connected by hinge joints allowing for thumb flexion. The most proximal thumb part **c** is pivotally mounted to the hand palm **a**. The axis of the latter joint is positioned orthogonal to the two hinge joints and therefore, responsible to alternate the thumb between reposition and opposition. Two strings are responsible for the thumb movement. String **m** is attached at the most distal thumb segment and is guided through all thumb segments until it is fixed to the drum **j** within the hand palm **a**. This string causes thumb flexion, when tensioned. The other string **g** is mounted to thumb section **c** at position **h**. Its other end is fixed to a second drum **n**. When string **g** gets tensioned, the thumb gets rotated to its opposed position due to its guiding. As soon as the tension in cable **g** is released, torsion spring **f** brings the thumb back to its original lateral position.
Drum **q** is fixed to the shaft **i** and thus, follows its rotational movement. In contrast to this, drum **n** can be shifted on or away from the shaft **i**. It is solely rotates with shaft **i**, when drum **n** is coupled to drum **q** by tight fit. A spring **q** generally pushes drum **n** away from drum **j**. Therefore, normally drum

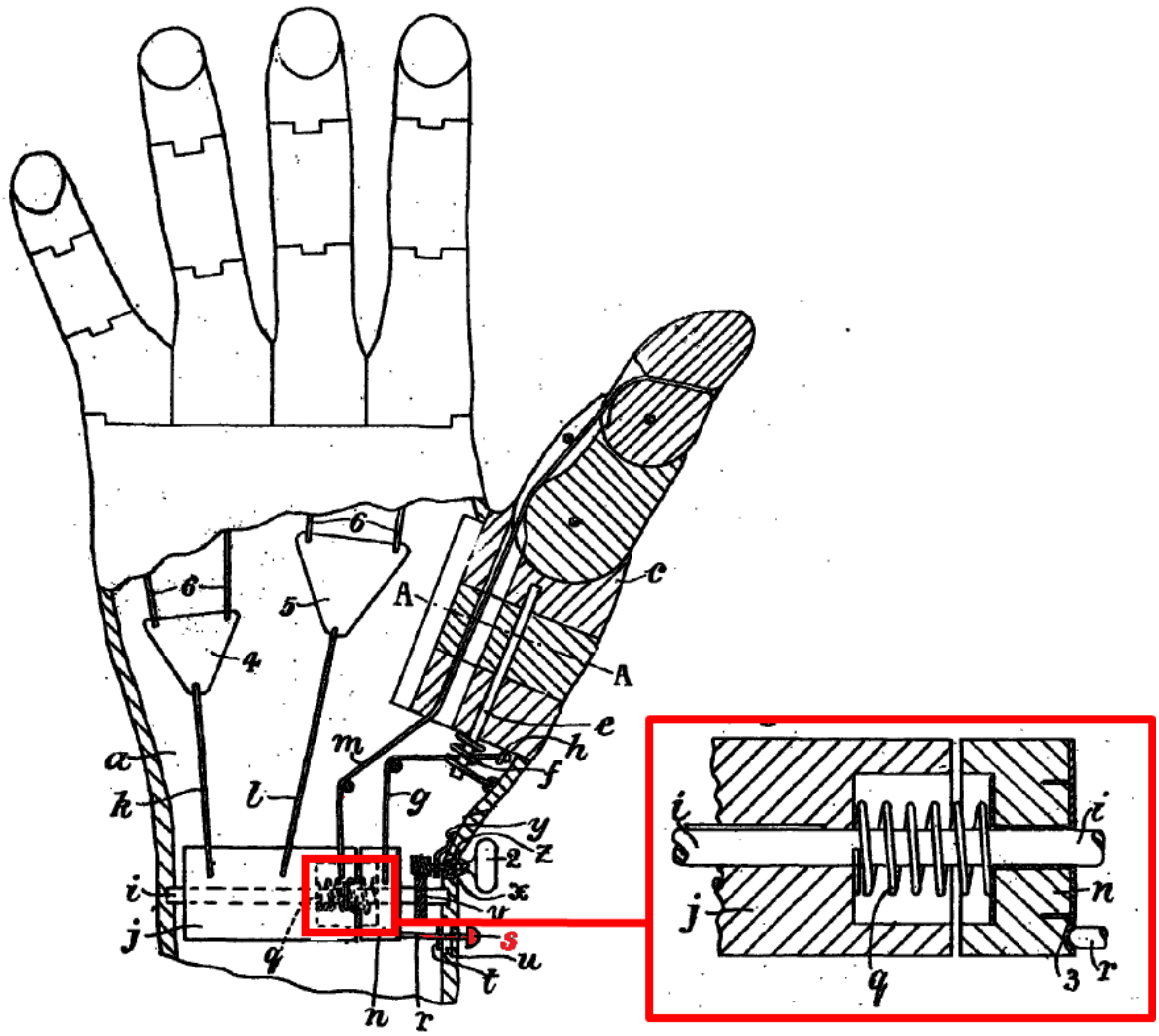

Figure 30: Hand mechanism of *GB 116,968* (extracted from [67])

n does not follow the rotation of shaft **i**.
When the amputee pushes knob **s** inwards with a slight turning movement, the drum **n** is moved against the force of spring **q** into connection to drum **j**. Due to the inward push of knob **s** pin **t** gets shifted out of its recess in the hand wall. The rotation of **s** leads to the pin **t** not aligning with its recess anymore. In contrast, it exerts force on the prosthetic wall and hence, prevents spring **q** to decouple drum **n** from drum **j**.
The finger mechanism is also attached to drum **j** and hence actuated by rotational movement of shaft **i**. The latter in turn is driven by a worm-wheel-system **v** & **z**, which passes to the outside of the prosthetic hand. On the outside a lid **2** is positioned on the worm **z**, to which the control cable is attached to [9][67].

The prosthetic hand patented as *US 7,361,197* by R. C. Winfrey is based on a similar principle as the just described one. It also comprises two control cables. One control cable is used to manipulate the fingers, the other one operates the thumb movement. Latter consist of rotational movement in the artificial carpometacarpal joint of the thumb as well as flexion in the metacarpophalangeal joint and the interphalangeal joint. When the control cable is tensioned, the thumb is rotated out of its lateral position towards its opposed position. The rotational movement is stopped either by the thumb

[9]In the patent no information is giving regarding the return mechanism for finger and thumb extension as well as for the control cable. However, this can be solved easily by implementing torsion springs at the lid **2** as well as the hinge joints of the finger and the thumb.

reaching its opposed position or by an opposing force preventing further rotation. When the rotational movement is stopped, additional force exerted on the cable leads to flexion of the metacarpophalangeal joint followed by the interphalangeal joint.
The thumb mechanism of this prosthetic hand is illustrated in Figure 31.

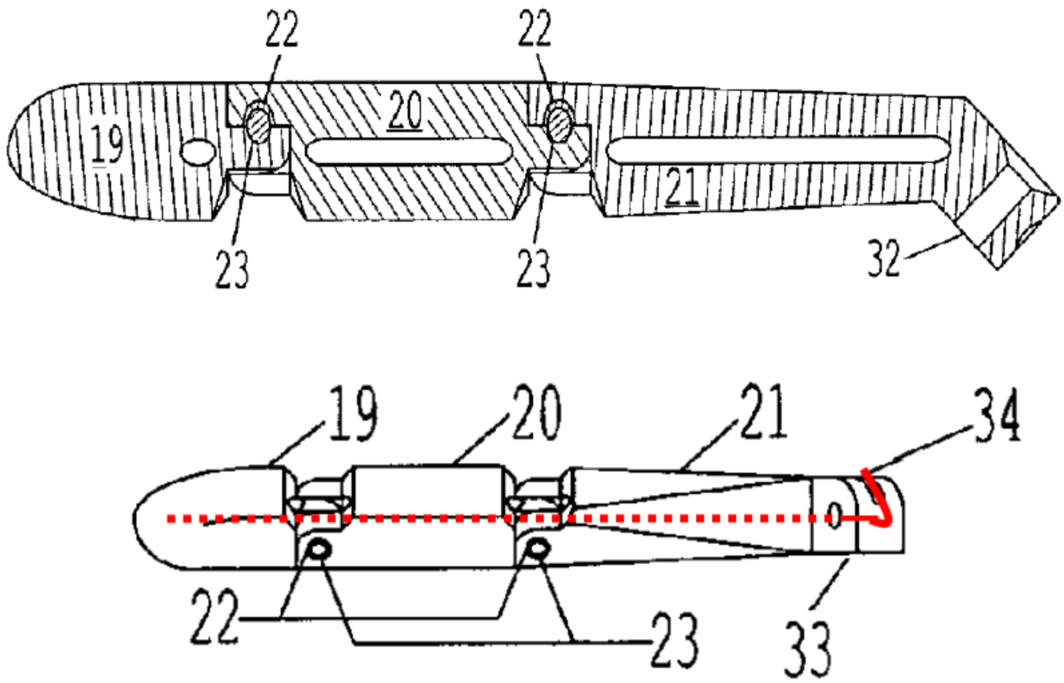

Figure 31: Thumb mechanism of *US 7,361,197* with control cable marked red (adapted from [68])

The thumb consist of three components **19**-**21**, which are connected by hinge joints **22** representing the metacarpophalangeal joint and the interphalangeal joint. The most proximal thumb component **21** comprises a segment aligned in an 45 degree angle to the remaining ones. In this part the carpometacarpal rotary joint **32** is located.
A string (marked red in Figure 31) is guided through all three components until hole **33**,where it leaves the interior of the thumb. Outside the string is routed through a groove **33** around the rotary joint **32**. Hence, the cable force acts tangential to the joint causing the rotation of the thumb. As stated earlier, the flexion of the other joints starts after thumb rotation having ended. These successive joint movements can be generated by allocating different values of resistant torques to the joints. The carpometacarpal joint has a low resistant torque applied to. Hence, its movement will already be initiated at low cable force values. The resistant torques are implemented by the passive elements, which are also responsible to drag the hand into its default state when the amputee has stopped its control motion. In the patent it is suggested to either use torsion springs or to adapt the thickness of the elastic glove material to achieve different torque values.
Comprising, in this device the thumb first of all tends to rotate to its opposed position. Hence, the amputee can conduct a pinch grip, when additional force is exerted on the cable causing the metacarpophalangeal joint and the interphalangeal joint to flex. However, having a force opposing the motion of the metacarpophalangeal joint at low cable tension, the thumb is forced to stay in its lateral position leading to lateral grasp [68].

Underactuated hands

In the so far presented devices, the fingers are generally coupled leading to the fingers always moving the same amount. Consequently, especially VO devices cannot be used to securely grasp irregularly shaped objects despite different grasp types. In order to do so, a solution is required, in which force from the control cable is transmitted to the five fingers in an adaptive manner. Since the rotation of the individual finger will vary depending on the shape of the object, multiple grip patterns can be accomplished.

Windler-Budzinski or Stodola have already applied this principle to their body-powered hands [51]. In current literature this functional principle, described as *underactutated*, has been revisited multiple times. In the following, the solution of underactuation will be introduced and some prototypes, illustrating how this principle can be implemented, will be described. A device is underactuated, if it comprises less actuators than the number of operators it facilitates [10, 69, 70]. This is often the case in hand prostheses, where the four fingers are operated by one control mechanism. When the fingers always move the same distance, no stable grip is achieved when grasping an irregularly shaped object. With "*underactuated hands*" a stable grip is achieved due to the fingers being able to adjust to the shape of the object. This is realized by differential coupling of the fingers. In differential coupling force transmission is adapted depending on opposing forces. Initially force is distributed among all fingers equally. As soon as one finger is in contact with an object, further applied force is shifted to the remaining fingers [69, 71]. In this way different grip patterns can be achieved easily. When grasping a big object, all fingers will finally make contact with the big object and a power grasp will be achieved. However, when a precision grip should be applied in order to pick up a pen, force will be distributed equally among all fingers until thumb and index finger make contact with the pen. If actuation force is still exerted, it will solely be distributed between middle, ring and small finger enabling these finger to close further. In this way, underactuation can be solved while implying natural adaptive grasping and hence, multiple grip patterns. There exist a big variety of solutions of differential coupling [72]. In the following the principles of "*floating pulleys*" , "*wiffle trees*" or a combination of both principles will be presented [71].

"*Floating Pulleys*"-mechanism

In the "*floating pulleys*"-mechanism force distribution is adapted by the excursion of tendons guided by pulleys [69]. Gosselin et al. [73] applied this principle in his design of the body-powered prosthetic hand is visualized in Figure 32.

The mechanism comprises two stages of pulleys, each vertically movable within its guide rail and each driving a tendon. The first stage comprises one pulley, to which the control cable [10] (marked green in Figure 32) is attached to. When the control cable is tensioned it drags the pulley in proximal direction. The pulley of the first stage affects two other tendons: the tendon of the first stage (marked blue in Figure 32) and the thumb tendon (marked purple in Figure 32). The thumb tendon is attached to the center of rotation of the first stage pulley. Consequently, when the pulley moves in proximal direction it drags the thumb tendon along causing thumb flexion. The tendon of the first stage runs inside the groove of the first stage pulley and its ends are each attached to the center of rotation of a pulley of the second stage. Again these pulleys have a tendon (marked red in Figure 32) running in their grooves. The ends of the tendons of the second stage each reach to a prosthetic finger. Consequently, when the pulley as well as the tendon of the first stage are pulled in proximal direction by the control cable, the pulleys and the tendons of the second stage are dragged along. This leads to the prosthetic fingers to flex.

However, as soon as a finger contacts an object, the continuing pulling force is transferred to the adjacent finger by circulation of the tendon. If the index finger contacts an object, the resisting force prevents further flexion of the finger. Thus, the tendon side reaching to the index finger will not move along with further vertical movement of the pulley. This leads to circulation of the tendon from the middle finger side to the index side. Hence, instead of pulley **B** pulling down each side of the tendon equally, the pulley moves proximally and rotates counterclockwise. Consequently, it solely pulls the tendon part reaching to the middle finger [73].

If the index and the middle finger are both in contact with an object, the force balancing occurs in the

[10] In Figure 32 the control cable is named driving tendon

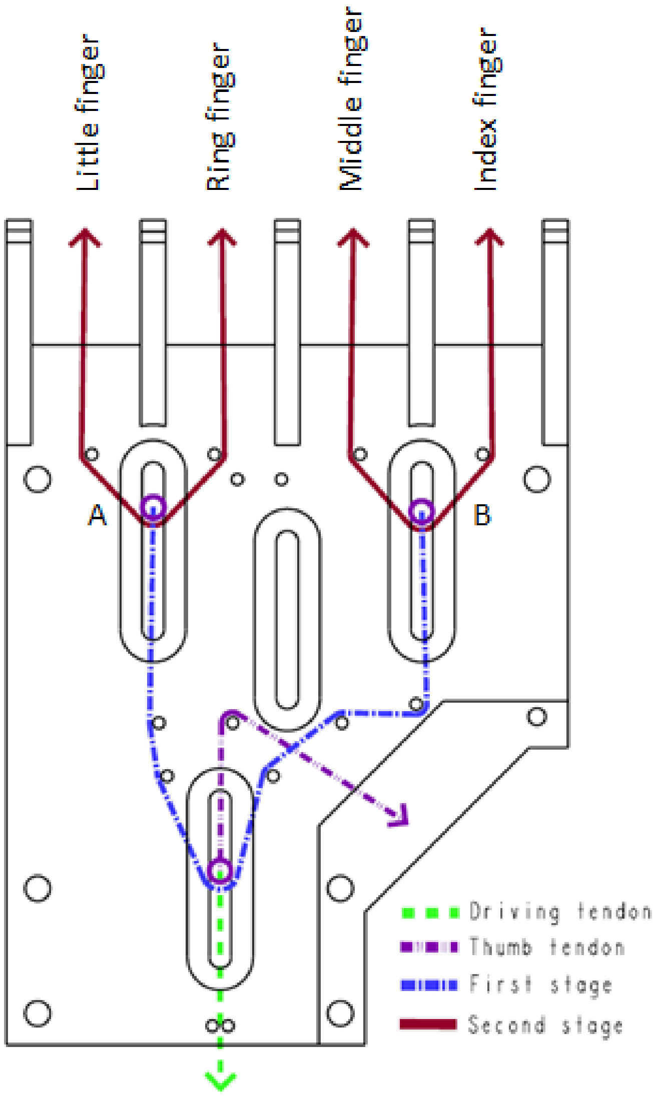

Figure 32: "*Floating Pulleys*"-mechanism (extracted from [73])

first stage leading to the cable circulation in counterclockwise direction [73].
The extension of the fingers are conducted passively. When control cable tension is realized, the pulleys and tendons are dragged into their default state by means of springs [73].
Patent *US 7,361,197* [68] also describes a device, to which this principle is also applied to.

"*Wiffle Trees*"-mechanism
This underactuation mechanism consist either of floating bars or floating triangular-shaped parts. When latter are used, the mechanism is also called "*seesaw*"-mechanism. Independently on the shape of the floating parts, adaptation is accomplished by tilting movements of the floating parts.
The "*wiffle trees*"-mechanism has been applied to the hand designed by Laliberté et al. [74], the hand designed and patent by Baril et al. [69, 70], the hand patented by McNaught [75] or the hand designed by de Visser & Herder [76] [11]. The "*wiffle trees*"-mechanism will be illustrated on the prototype of

[11] In the prototype designed by de Visser & Herder [76] the differential control slightly deviates from the other mentioned "*wiffle trees*"-mechanism. Instead of having two levels of floating parts, solely one triangular shaped part is used. On the top of this triangle the thumb, index finger and middle finger are attached. On the bottom of the triangle the control cable is fixed. Consequently, force adaptation will only be conducted by the thumb, index finger and middle finger. The general principle of

Laliberté et al. [74] as illustrated in Figure 33 .

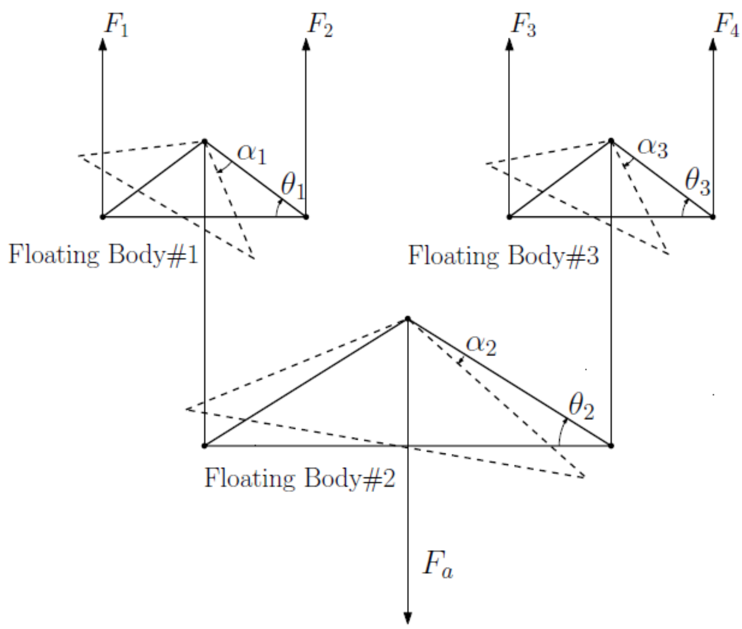

Figure 33: "*Seesaw*"-mechanism (extracted from [74])

Two levels of triangular shaped floating bodies build the underactuation mechanism. The upper level comprises two smaller floating bodies (*Floating Body # 1* and *Floating Body # 3*). *Floating Body # 1* has e.g. the tendon on its left side reaching to the little and the right tendon reaching to the ring finger. Consequently, little finger and ring finger are coupled. *Floating Body # 3* links the middle finger and the index finger in the same way. The small floating bodies are connected by the bigger *Floating Body # 2*. One tendon connects the left side of the *Floating Body # 2* and the tip of the *Floating Body # 1*. A tendon on the right side of the *Floating Body # 2* reaches to the tip of the *Floating Body # 3*. To the tip of *Floating Body # 2* the control cable of the prosthesis is attached.
By pulling the control cable, the force will be equally distributed among the four fingers. However, if a finger (e.g. the index finger) makes contact with an object, the force distribution alternates in *Floating Body # 3*. The floating body tilts to the tendon of the middle finger facilitating it to continue closing. However, in the bigger floating body force will still be equally transferred to *Floating Body # 1* and *Floating Body # 3*. Consequently, little finger and ring finger can proceed to close. However, when two adjacent fingers have made contact (e.g. index and middle finger), *Floating Body # 2* will tilt to the side of fingers not in contact so those fingers can continue to flex. In the described example *Floating Body # 2* transfers force solely to *Floating Body # 1* [74].
In Laliberté's et al. [74] design the cable driving thumb flexion and extension is directly coupled to the control cable. In addition, the thumb can be switched passively between a lateral and a opposed position [74].
The same underactuation mechanism was applied by Baril et al. [69] on their prototype. This device was further equipped with a mechanical selector. By means of the sound hand, this selector can be used to choose between three different grip patterns. Depending on the grip type selected, force transmission to particular fingers are directly decoupled by blocking its tendon. For this each tendon is provided with a small ball, which can be clamped by the mechanical selector. To the fingers, which are blocked by the mechanical selector, no force will be transmitted at any time and thus, will remain to be extended [69, 70].

this underactuation method of adaptation by floating part tilting does not change. However, in this case the tilting in three instead of merely two dimensions is considered.

Combination
In Yale Hand designed by Belter & Dollar [71] the "*floating pulleys*"- and the "*wiffle trees*"-principle are combined. The mechanism comprises one balance bar, five pulleys and three cables as illustrated in Figure 34.

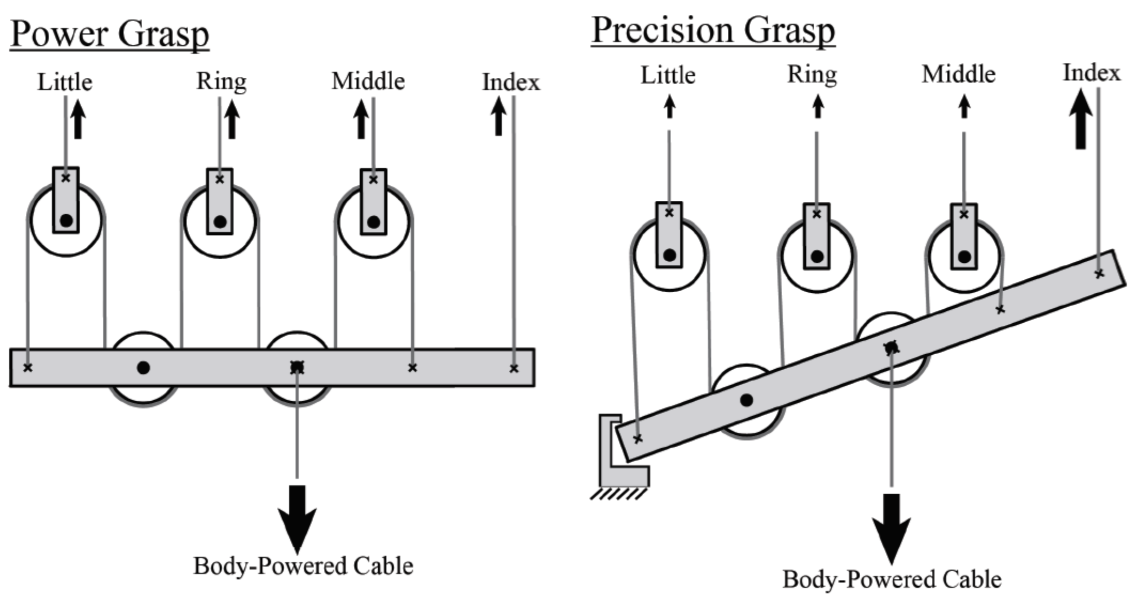

Figure 34: Constallation of the Yale Hand's differential mechanism for power grip (left) and position grip (right) [71]

A balance bar serves as coupling mechanism of the control cable and the mechanical replacements of the fingers. Middle, ring and little finger are all represented by a floating pulley. They are directly connected by a cable, which is fixed to the balance bar. Starting at cable fixation at the left end of the bar the cable passes the floating pulley representing the little finger. From there it approaches the balance bar, where a fixated pulley deflects the cable towards the ring finger pulley. From there it again reaches to the bar fixated pulley, which directs it to the middle finger pulley. Finally, it is attached on the balance bar again. The index finger is solely represented by an individual cable, which is tied to the right end of the balance bar. The control cable is attached in the middle of the floating bar being orientated in opposite direction to the other cables.
By pulling the control cable with the balancing bar horizontally orientated, equal force is distributed to each finger. However, if little, ring or middle finger makes contact with the object before the others, additional force will be deflected to the other fingers enabling them to close further. In this way a power grasp can be accomplished.
The *Yale Hand* is designed to facilitate a fine controlled precision grasp. By applying an external toggle, the balancing bar gets locked in a tilted position. Since the left side of the bar is blocked, solely the right side of the balance bar can conduct movement. Consequently, pulling on the control cable leads to a great extent to flexion of the index finger as illustrated in Figure 34. The thumb has been left out from this adaptive control mechanism. In this prototype, a cable driving thumb flexion and extension was directly coupled to the control cable. Furthermore, the position of the thumb can be changed passively enabling lateral, precision or power grasp [71].
In an advancement of the just described prototype, the toggle was replaced by the thumb positioning defining the position of the balancing bar and thus the following grasp type [71].
An other example of a combination of the underactuation principles is applied in the prosthetic hand designed by Dollar & Howe [77].

4.2.2. VO/VC-hands

As mentioned before in Chapter 3.2, current body-powered prostheses are classified either as '*voluntary-opening*" (VO) or "*voluntary-closing*" (VC). Consequently, the body-powered prostheses can only be controlled voluntarily in one way. The reversed direction is conducted by means of a passive element such as springs or rubber bands [2].
The VO- as well as the VC-mode have each its advantage over the other one. When using a VO prosthesis, the amputee exerts force to open the terminal device. To continuously hold an object, the amputee relaxes. Consequently, prolonged grasping does not require any energy from the amputee. Though, the applied and maximal applicable force cannot be controlled by the amputee. Instead it is predetermined by the characteristics of the passive element and the size of the object to be gasped [2, 38, 78].
On the contrary, when using a VC prosthesis, the applied force can be proportionally controlled by the amputee and the maximum force depends on the physical condition of the user. However, in order to hold an object for a longer time period, the amputee needs to provide energy permanently. This can be very tiring. To prevent fatigue, some VC devices have a lock to secure the current degree of closing [2, 6, 38, 78, 79]. In addition to the advantage of active force control the proprioceptive feedback supplied by the VC prosthesis is intuitive: bigger body movements lead to higher prehension force [6]. In VO prosthesis, the feedback is reciprocal and hence, it is less intuitive.

Since VO- as well VC-mode are desirable, research has been conducted designing a device to facilitate both modes [2]. By enabling both modes the number of DoF of the prosthetic hand is not increased. However, it ensures the amputee to be able to control both prehension directions actively and hence, facilitates the amputee with more awareness of its prehension motion. Since this is highly beneficial for the patient, devices facilitating both modes will be depicted in this literature review as well.

LeBlanc et al.[80] have constructed a prosthetic hook, which comprises two stationary legs **A** & **C** and one movable leg **B.** In the default state, the movable leg **B** is pressed against the stationary leg **A.** When the amputee tensions the control cable, the leg **B** moves towards the stationary leg **C.** If the object to be handled is positioned between the legs **B** & **C**, it is handled in VC-mode. However, at the same time it is also possible use the arising space between leg **B** and leg **A.** When cable tension is released an object can be clamped between leg **B** and leg **A.** Hence, the movement can be described as VO [80].

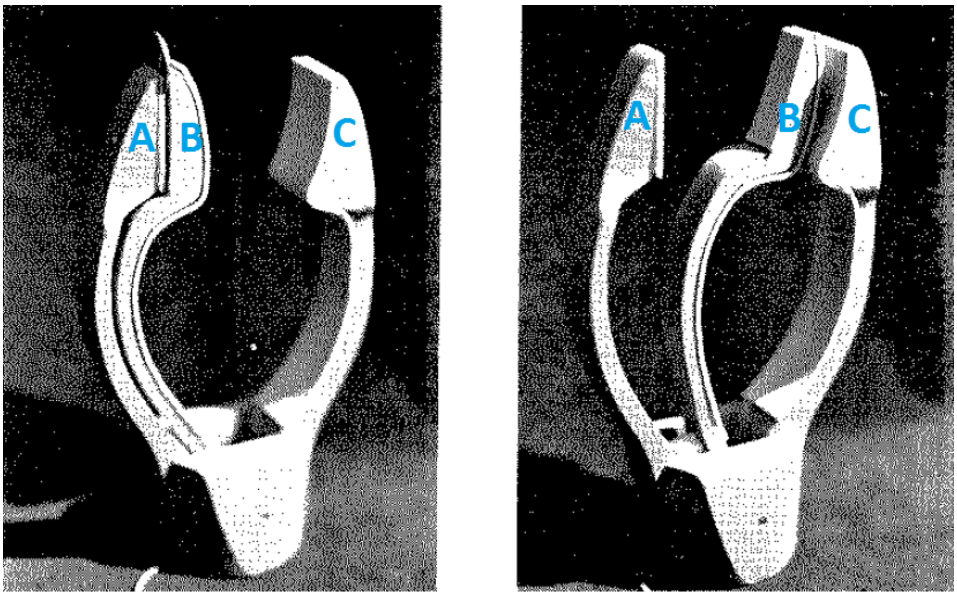

Figure 35: LeBlanc's design in VO-mode (left) and in VC-mode (right)(extracted from [80])

To sum up LeBlanc et al. [80] have created a device, which facilitates VC- and VO-mode instantaneously. However, the object size is restricted to small objects for the VO-mode. LeBlanc et al. [80] describe this fact as the VO-mode supporting pinch grasp and VC-mode palm grasp.

A few more devices have been developed, which support VO- as well as VC-mode. However, they require a mode-altering mechanism. Their mechanisms can be categorized into four different types: "*Reversed Body Movement*", "*Sequential Switch*", "*Variation in the course of the Control Motion*" and "*Manual Switch Manipulation*" At least one device of each category will be depicted in the following.

Reversed Body Movement

One possibility to facilitate both VO- and VC-mode is to design the mechanism of the prosthesis in such a way that the amputee can use a defined body movement to voluntarily open the prehensor and the reversed motion to voluntarily close it. Prosthetic devices with rigid connections or rotation controlled hands are generally able to ensure such a two-way controlled mechanism. As outlined in Section 3.2.3 rotational controlled hands are: *Arm of Dalisch from 1857*, the *Hand of Härtel*, the *Rotational controlled hand of Leiter*, the *Zawodnik hand* or the *Arm of Erlacher* [46].
Examples of rigid connected prostheses, which facilitate VO as well as VC, are the *Hand of Charriére*, the *Hand of Troschinski*, *Elbow controlled hand of Leiter*, the *Arm of Mietens* or the *Arm of Jaks*. In these prostheses, the flexion of the elbow causes device opening and elbow extension device closing [46].

W.T. Carnes has filed the two patents *US 999,484* and *US 1,046,966* securing prosthetic hands, with which prehension can be controlled both ways actively . The two-way control of these devices is based on two cables (*Seil 1* marked yellow in Figure 4.2.2 and *Seil 2* marked red), which are operated by reversed body movements [81, 82]. Even though the concrete mechanisms of the two devices vary, the fundamental control principles comply. Because of patent *US 1,046,966* being an advancement of *US 999,484*, solely its mechanism will be explained in more detail in the following. The hand of *US 1,046,966* is illustrated in Figure 4.2.2 [12].

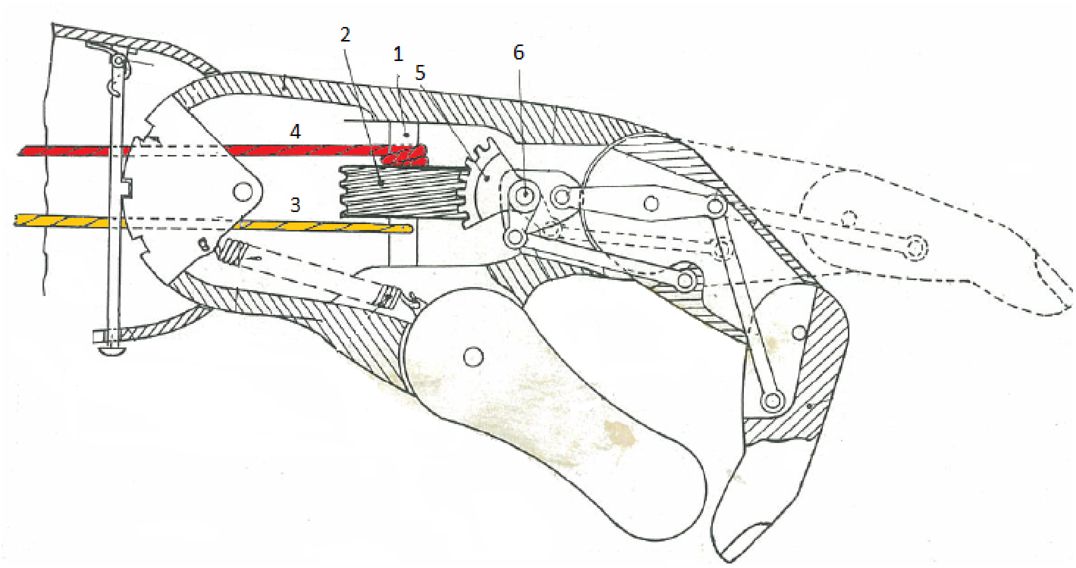

Figure 36: *Carnes Hand* for below-elbow amputees with flexed (solid lines) and extended finger (dashed lines) (adapted from [51])

[12]The hand prosthesis designed by W.T. Carnes also facilitates wrist rotation as well as wrist flexion. The concrete mechanism of the wrist movement will be explained in Chapter 5.2

Each finger consists of rods, which are rotatably connected by pins. The rods drive the phalanxes of the fingers. When the rods are pulled in proximal direction, the phalanxes are rotated in clockwise direction causing the hand to close. In contrast to this, pushing the rods in distal direction causes hand opening. The movement directions of the rods are dependent on the rotational direction of the worm shaft **1**. A worm wheel segment **5** engages with the worm **2** of shaft **1**. This worm wheel segment **5** is positioned on shaft **6**, to which the proximal figner rods are attached to. When shaft **1** and its worm **2** rotate in clockwise direction, the worm shaft segment **5** is moved counterclockwise. Hereby, the rods are pulled in proximal direction causing the hand to close. When the worm shaft **1** rotates counterclockwise, the reversed movement is initiated.
The direction of the worm shaft **1** in turn depends on the control cable **3** or **4** being pulled. Two control cables **3** & **4** are winded in opposed directions around the worm shaft **1**. Consequently, when the control cord **3** is pulled, it unwinds and rotates the worm shaft **1** in counterclockwise direction. In the meanwhile the other control cord **4** coils up. When control cord **4** is tensioned, the reversed action happens [51, 82]. The harness design related to the W.T. Carnes' prosthesis is shown in Figure 37.

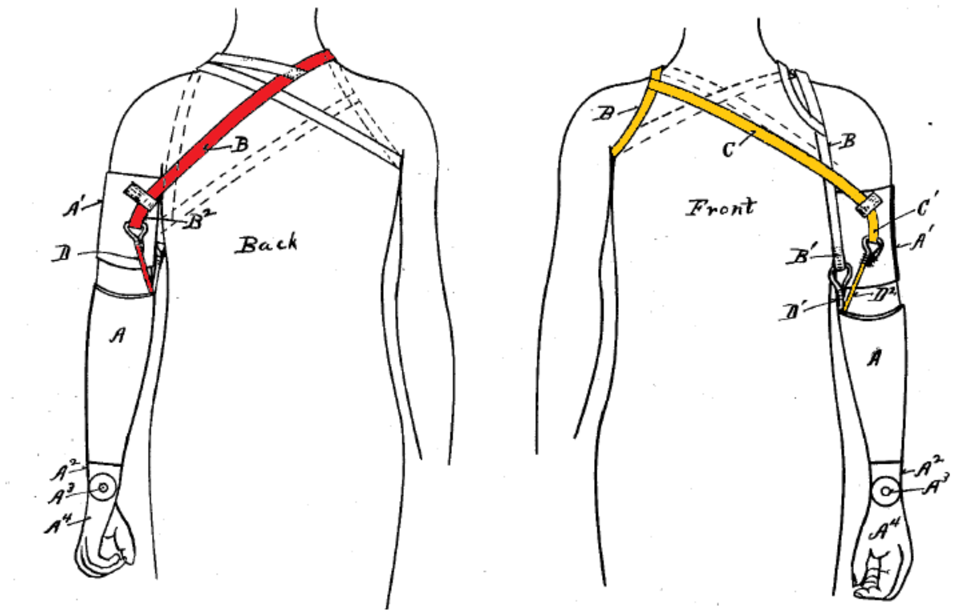

Figure 37: Harness design of *Carnes Hand* for below-elbow amputees (extracted from [82])

The opening control cord **3** exits the socket as cable $\mathbf{D}^1$ on the ventral side of the arm. It passes the elbow joint and is guided across the chest to the harness loop **B** positioned on the contralateral shoulder. In contrast, the closing control cord **4** leaves the socket as cable **D** on the dorsal arm side. It is directed across the patient's back and converges into the harness loop **B**. Consequently, shoulder retraction leads to hand opening and the reversed shoulder protraction to hand closing [82].

Sequential Switch

Above-elbow amputees also require a replacement of the elbow. Consequently, they need an additional control motion for this new joint. In order to have an applicable cable for the elbow replacement, W.T. Carnes changed his just described hand design in such a way that solely one cable is required for both prehension modes. The mechanics of the fingers is left unchanged. However, instead of having two cables attached to the worm shaft **1** to control the two different prehension modes, the hand comprises solely one control cable and a switching mechanism, which varies the mode of the control cable sequentially: one control motion leads to device opening and in the next repetition it causes device closing. The altering mechanism responsible for the sequential mode switching of the *Carnes Hand* is illustrated in Figure 38.

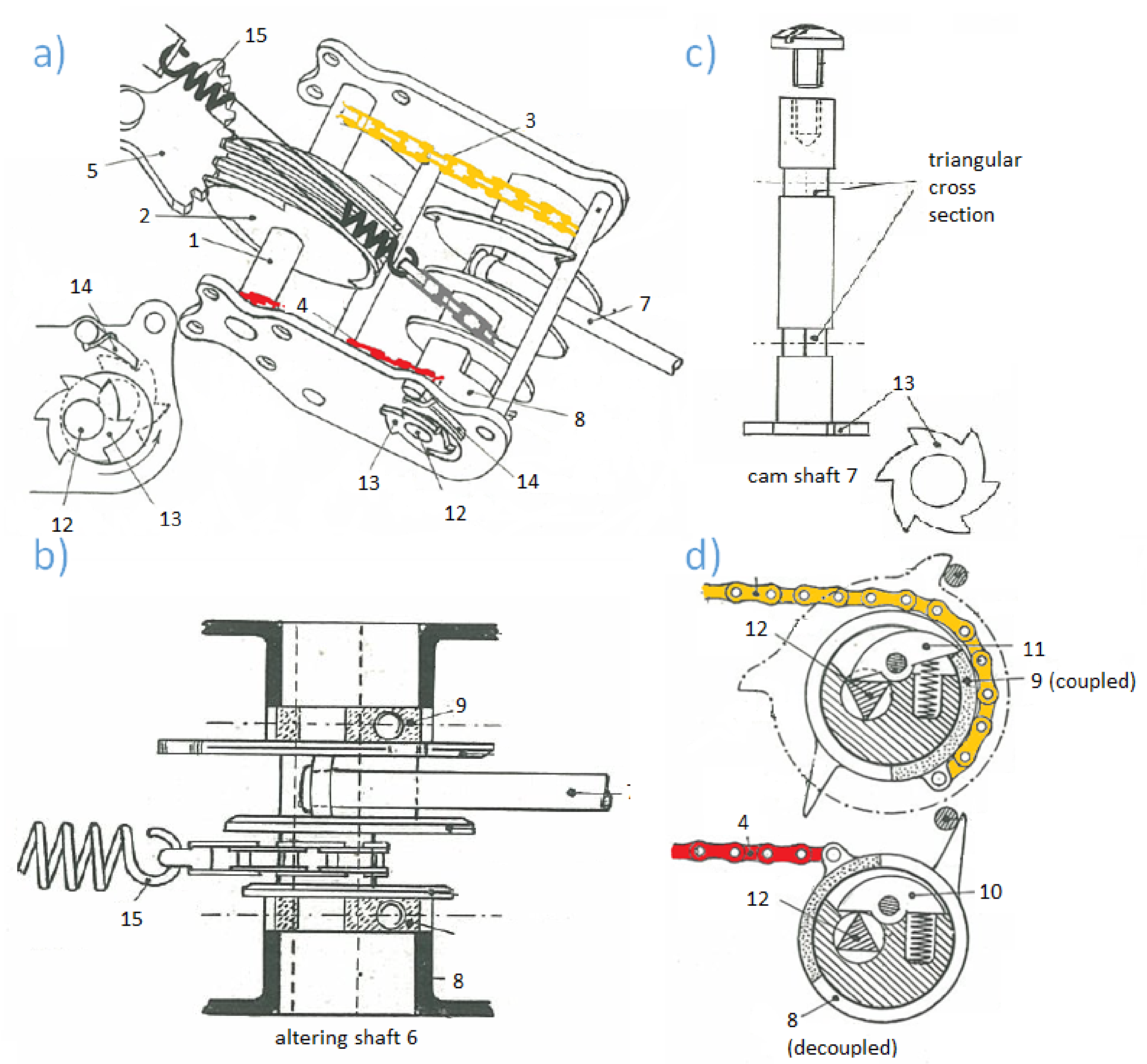

Figure 38: Altering mechanism of *Carnes Hand* for above-elbow amputees : a) complete, b) altering shaft, c) cam shaft, d) cases(adapted from [83])

Carnes developed the hand for above elbow amputees in such a way that one control cable is used to conduct prehension movement as well as mode-switching. This is achieved by means of an altering mechanism, which varies the prehension mode of the TD after each pulling cycle [13].
The finger mechanics of the prosthesis for below-elbow amputees remains the same for the design for above-elbow amputees. However, the worm shaft **1**(also marked **1** in Figure) is now part of the altering mechanism. Instead of having two control cables driving the worm shaft **1**, the two chains **3** and **4** determine the movement of the shaft **1**. The chains **3** and **4** are each positioned on opposite sides of the worm **2** and have reversed windings. Furthermore, they connect the worm shaft **1** with the altering shaft **6**, to which the control cable **7** is attached to. When the cable **7** is relaxed, it is wound once around the altering shaft **6**.
The chains **3** and **4** are each attached to a case **8** and **9**, which are positioned on the altering shaft **6**. One case at the time is coupled to the altering shaft **6** and the other one rotates independently it. After each pulling cycle, it is alternated which case is coupled to the altering shaft **6**. The coupling of the cases **8** and **9** are conducted by the ratchet levers **10** and **11**, which are positioned inside the

[13] A pulling cycle consist of cable tensioning and the following force releasing.

cases. The ratchet levers **10** and **11** are manipulated by a cam shaft **12**, which lies within the altering shaft **6**. The cam shaft **12** has two parts with reversed, triangular cross sections. The ratchet levers **10** and **11** each are pressed against one of these parts of cam shaft by a spring. Depending on which part of the triangular cross section the ratchet levers **10** and **11** contact they are either coupled to the altering shaft **6** or keep its independent rotation (see Figure 38 d)). When ratchet lever **11** is in contact with a surface, ratchet lever **12** lies on an edge. In this configuration ratchet lever **11** will couple the case **9** to the altering shaft **6**. Hence, pulling the control cable **7** leads to rotation of the altering shaft **6** and the case **9** in clockwise direction. The chain **3** connecting the worm shaft **1** and the case **9** will be pulled in proximal direction and will wind on the case **9**. As a consequence, chain **3** rotates worm shaft **1** in clockwise direction. This leads to hand closing. Since the reversed winded chain **4** is also attached to worm shaft **1**, chain **4** winds on the worm shaft **1** while chain **3** unwinds. Consequently, chain **4** is moved into distal direction causing an independent rotation of case **8** in counterclockwise direction.
When the force on the control cable **7** is released, TD mode switching is initiated. For this, the cam shaft **12** is mounted eccentrically within the altering shaft **6**. When control cable force is released, the altering shaft **6** is rotated back to its default state by means of spring **15**. During this, the ratchet **13** of the eccentrically mounted cam shaft **12** rams against pawl **14**. This causes the ratchet **13** and thus, the cam shaft **12** to rotate around 60°. Consequently, the ratchet lever **10** will move on a surface and the ratchet lever **11** will move on an edge of the triangular cross section of the cam shaft **12**. This leads to coupling of case **8** to the altering shaft **6** and decoupling of case **9** from it. Hence, next time force is exerted to the control cable **7**, the worm shaft **1** will be rotated in opposite direction and thus, the hand will be opened [46, 51, 83].

Variation in course of the Control Motion

Another way to facilitate mode-altering is the mode varying in the course of the control movement [2]. In the elbow controlled *Hand of Dalisch* the mode alters in the range of elbow flexion. When the amputee has his elbow fully extended, the prehensor is totally closed. Flexing the elbow up to 45° opens the prehensor. Further flexion up to 90° causes device closing [46].

In Figure 39 the prototype designed by Nelson et al., lso varies in the range of the operating motion , is illustrated [80, 84–86].

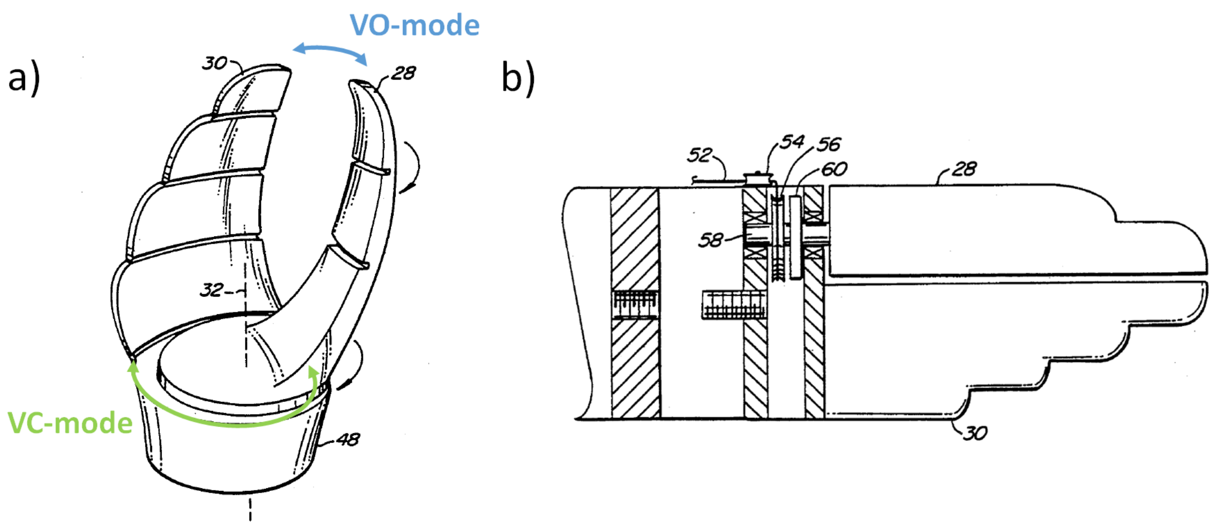

Figure 39: Rotational thumb faciliates mode switching depending on the elongation of the control cable; showing the device (a) outer and (b) interior (adapted from [86])

This prototype has a rotatable thumb **28** and a stationary part **30**, which represents the other four fingers. The control cable **52** is guided by the pulley **54** into the inside of the terminal device. There the cable is winded around the pulley **55**, which is mounted to shaft **58**. The rotating plate of the thumb **28** is also coupled to the shaft **58**. Consequently, the thumb follows the clockwise rotation of pulley **56**, when control cable **54** is tensioned. Once the tension of cable **54** is released, the spiral spring **60**, which is also positioned on shaft **58**, moves the thumb back to its original position [86].
When no force is applied to the control cable, the thumb **28** contacts in its default state the prosthetic palm **30** (Figure 40 a)). Once the amputee starts to manipulate the control cable, the thumb **28** is rotated clockwise thereby creating a space, in which an object can be positioned. When cable tension is released the spiral spring **60** drags the thumb to rotate back to its default state. Hence, the object can be clamped. Consequently, the initial behavior of the device can be described as VO (Figure 40 b)).
When the amputee applies a higher force on the control cable, the thumb **60** rotates further approaching the palm part **30** from the other direction. Hence, an object can be grasped in a VC-mode as illustrated in Figure 40 c) [86].

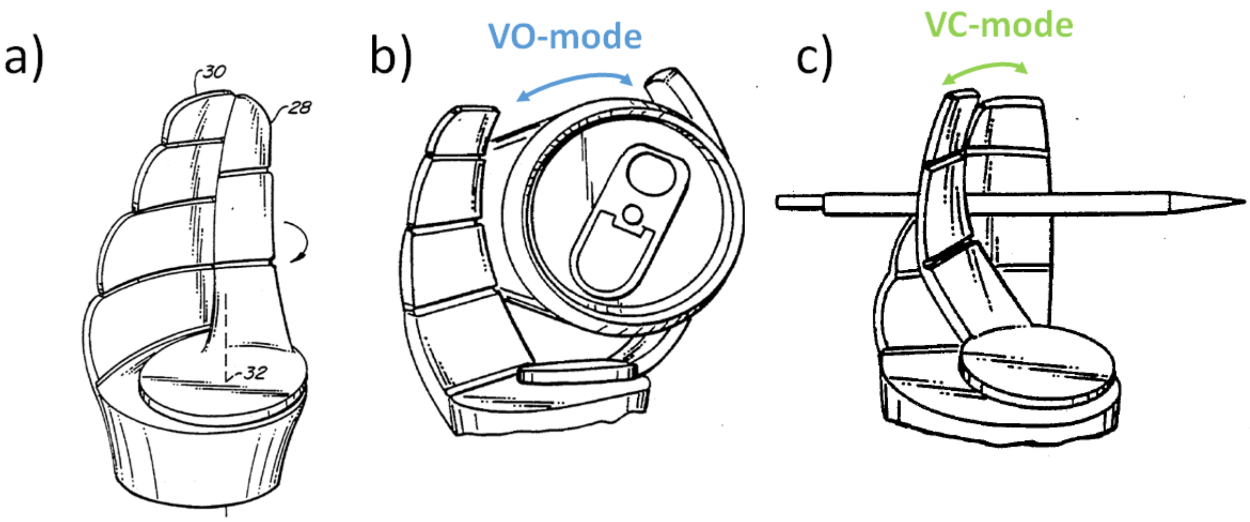

Figure 40: Change of grasp type in the course of control motion with a) default state, b) palm grasp and c) pinch grasp (extracted from [86])

Consequently, in the range of the control motion, the device switches from voluntary-opening to voluntary-closing mode. Due to the shape of the palm **30** a palm grasp is imitated when using the device in the VO-mode and a pinch grasp in the VC-mode [80, 84–86].

One conceptual solution described on the Website of *The Open Prosthetic Project* [87] is based also on this mode-altering principle as can be seen in Figure 41.

In this concept the TD comprises a stationary leg **D**, a rotatory leg **C** and a lever **A.** The lever **A** is pivoted in point **a** and has the control cable **B** attached at its right end. When the control cable **B** is pulled, the lever **A** conducts a clockwise rotation.
On the left end of lever **A** there is a cam attached, which is inserted in the slotted hole of movable leg **C**. The cam can move freely within the slotted hole. Since the left leg **C** is pivoted around point **c**, movement of the cam leads to rotational movement of leg **C.** The direction of the leg rotation and thus prosthetic mode depends on the relative position of the cam to the lever's center of rotation **a**.
The default state of the hook is the closed position with the cam positioned at the proximal end of the slotted hole and the lever **A** in a tilted position (Figure 41 (1)). When force is exerted on the control

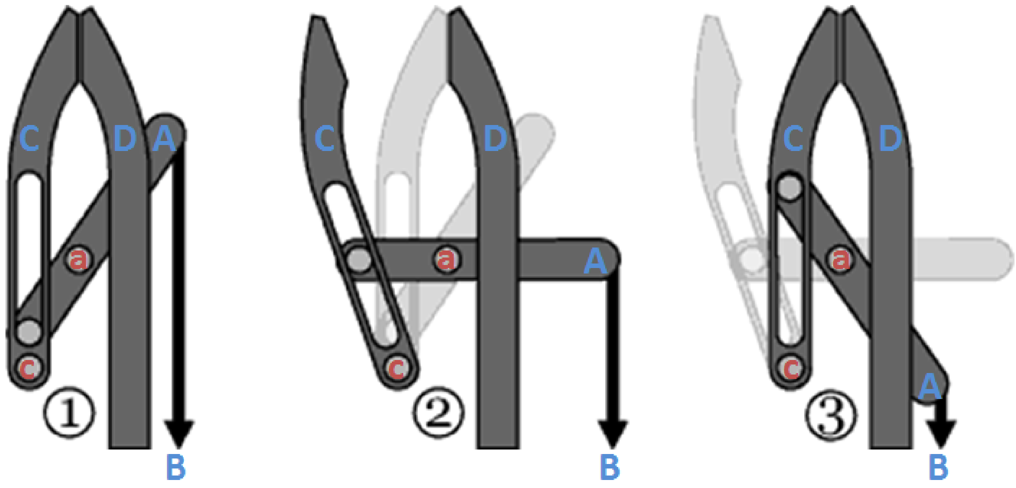

Figure 41: Conceptual solution of sequential mode-altering mechanism (extracted from [87])

cable **B**, it initiates clockwise rotation of lever **A**. The cam on the left end of the lever **A** moves within the slotted hole, pushing the left leg **C** into counterclockwise direction. Hence, the terminal device opens and can be described as VO. When the lever **A** is rotated into a horizontal position, the cam is leveled with the lever's center of rotation **a**. Then the maximum opening width of the TD is accomplished (Figure 41 (2)).
Additional force on lever **A** causes the cam to move further in distal direction and the cam surpasses the lever's center of rotation **a**. Thus, the cam pushes the left leg in clockwise direction causing TD closing (Figure 41 (3)) in VC-manner [87].
In the description of the principle two springs are mentioned. One spring is responsible to bring the control cable **B** back to its default state. The other one tries to keep the hook in closed position [87]. However no concrete information regarding the positions and mechanism of the springs are given.

Manual Switch Manipulation

In the last type of VO/VC-devices, the amputee can switch the mode of the prosthesis by operating a toggle with the sound hand.
The Open Prosthetic Project [87] has created the conceptual solution based on this idea as illustrated in Figure 42.

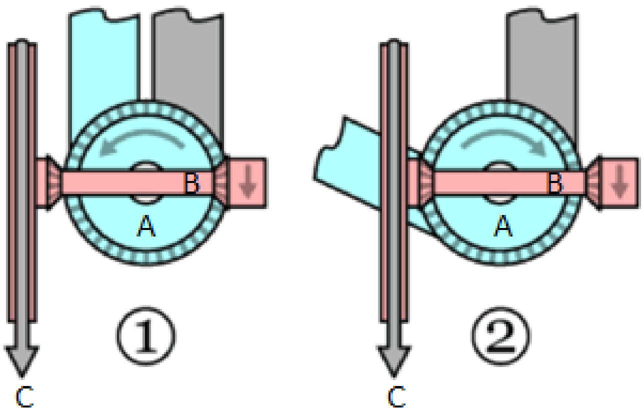

Figure 42: Conceptual solution of mode-altering mechanism using a switch (extracted from [87])

The legs of the hook are attached to the wheel **A**. The wheel is spanned by a shaft **B**, which has a pinion at each of its ends. A control cable **C** is attached to the left end of shaft **B**.
The wheel **A** is in contact with one pinion at the time. Depending on the pinion, the rotational direction of wheel **A** and thus the mode of the TD is determined.
When the VO-mode is desired, the right pinion has to contact wheel **A**. Then, the elongation on the control cable **C** causes a counterclockwise rotation of the wheel **A** and thus, TD opening (Figure 42(1)). By pulling the shaft to the right, the left pivot will make contact with the wheel **A** and the left leg will be moved to its maximal opening position. Force exerted on the control cable **C** will this time lead to a clockwise rotation of the wheel **A**. Hence, the TD will close (Figure 42(2)) [87]. This described mechanism is solely a fundamental idea of an altering mechanism. However, it requires further elaboration; for example it is not evident from the functional description by *The Open Prosthetic Project* [87] how the default position of the TD changes during mode switching.

In the prosthetic hand designed by Sullivan grasping mode altering is based on changing the path of the force flux in interacting gears [40]. The prosthetic device is shown as a whole in Figure 43 a). It consists of a stationary, upper gripper and a movable, lower gripper. The movable gripper is driven by a system of gears, which can be seen in Figure 43 b). However, the concrete gear arrangement varies depending on the position of the switch. This will be described later in more detail since it also determines the prehension mode of the TD.

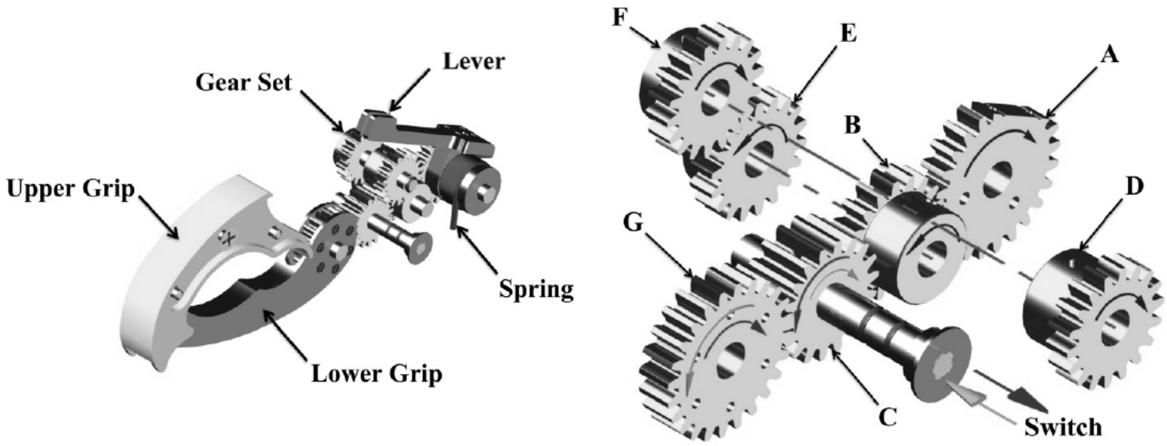

Figure 43: Mode-alternating hand designed by Sullivan as a whole (left) and illustration of the gear system (right)(extracted from [40])

To the most proximal gear **A** a lever is coupled to. It is responsible for the application of force to the set of gears. Therefore, the control cable of the prosthesis is attached to it as well as a torsion spring, which is responsible for resetting the device to its default state after cable relaxation.
The gripping mode of the hand is defined by the position of the switch, which influences the gear configuration since it is connected to the lateral movable gear **C**.
When the switch is pushed inwards, gear **C** interacts with gear **B**. Consequently, cable tension leads to the lever dragging gear **A** to rotate clockwise. This in turn causes gear **B** to rotate counterclockwise. Gear **B** drives gear **C**, which in turns moves gear **G** in counterclockwise direction leading to hand opening. Consequently, the hand is in VO-mode.
By pulling the switching toggle to its distal position the initially coupled gears **B** and **C** get disconnected. Ergo, no force can be directly transmitted from gear **B** to gear **C**. Instead the force flux is redirected through the gears **E**, **F** and **D**. When the control cable is pulled, gear **A** drives as usual gear **B** in counterclockwise direction. The gear **E** is mounted to the same shaft as gear **B** and hence, always follows its counterclockwise rotation. Due to the current gap between gear **B** and gear **C**, the gear **E** is required for a continues force flux. Gear **E** in turn engages with **F** and hence, drives it to rotated

clockwise. Gear **D** follows this movement as it is mounted to the same shaft as gear **F**. Because of gear **C** having a changed position, gear **D** now meshes with it and thus, causing it to turn counterclockwise. Consequently, gear **G** moves clockwise causing the lower grip to close the TD.
The sound hand is needed to control the switch. To prevent involuntary mode-altering, the switch has V-grooves, in which two ball end plungers are pushed into by means of springs. Hence, a pulling/pushing force of 1 - 1.5 N is required to change the position of the switch [40].

Veatch has filed the patent *US 2015/0021947* [88] also regarding a device comprising a stationary and a movable gripper leg, whose movements can be varied by operating a toggle with the sound hand. This time, toggle operation does not influence the force flux within the system, but it changes the point of the origin of the force as visualized in in Figure 44.

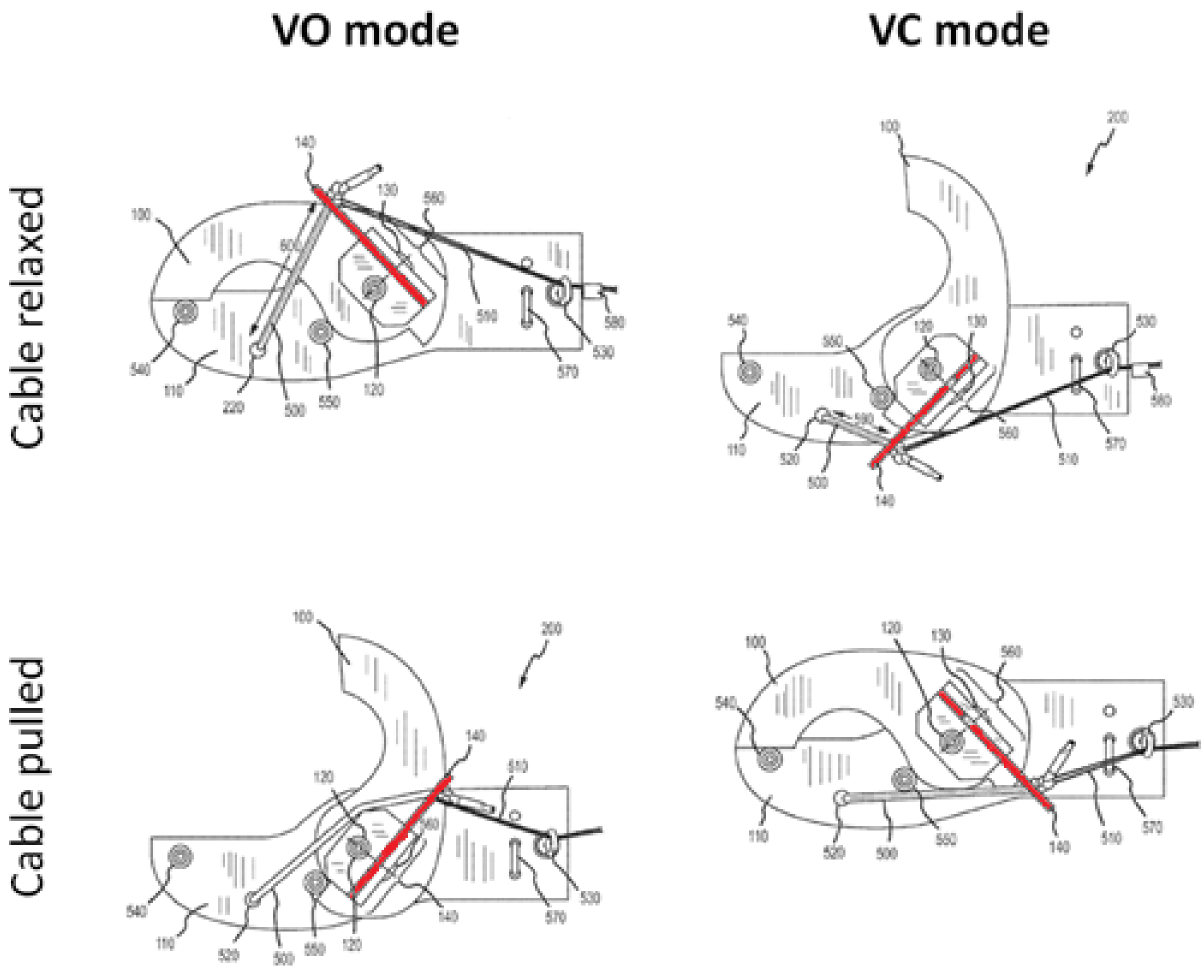

Figure 44: Veatch's mode-alternating terminal device (extracted from [88])

The control cable **570** is fixed to lever **140**. This in turn has spring **500** attached to, whose other end is fixed to the stationary gripper leg **110**. The lever **140** itself is mounted to the movable leg **100** and can be turned around axis **130**. By rotating the lever **140**, prehension mode of the TD is switched due to a changed route of cable **510**, of spring **500** and a changed spring preload.
In VO-mode the free end of lever **140** is positioned at the dorsal side of the TD. Consequently, the control cable **510** ends above the movable gripper leg **100**. The spring **500** stretches from its fixed point on the stationary leg **110** on the palmar side of the TD to the end of lever **140** on the dorsal side of the gripper. The gripper is closed in its default state. When the control cable is pulled, the upper

gripper leg **100** experiences a rotation in clockwise direction and hence, it is opened. Consequently, spring **500** gets tension. This tension is the driving force to reset the TD as soon as the control cable is released.
In VC-mode the free end of lever **140** is positioned at the palmar side of the TD. Hence, the control cable **510** stretches to the palmar side of the TD. Spring **500** stays solely on the plamar side of the TD. When the control cable **510** is relaxed, the gripper is opened with the spring **500** in a compressed state. As soon as the control cable **510** is pulled, the upper gripper leg **100** experiences a rotation in counterclockwise direction causing the gripper to close. Hereby, spring **500** gets tensioned. As soon as the amputee stops pulling the control cable, spring **500** drives the TD to its open position [88].

In the most current literature found regarding a VO/VC-device the mechanism also requires the sound hand for operation [38, 78, 79, 89].
A picture of the constructed prototype is shown in Figure 45. The working principle, which was already patented by Sensinger in 2014 [89], is illustrated in Figure 47.

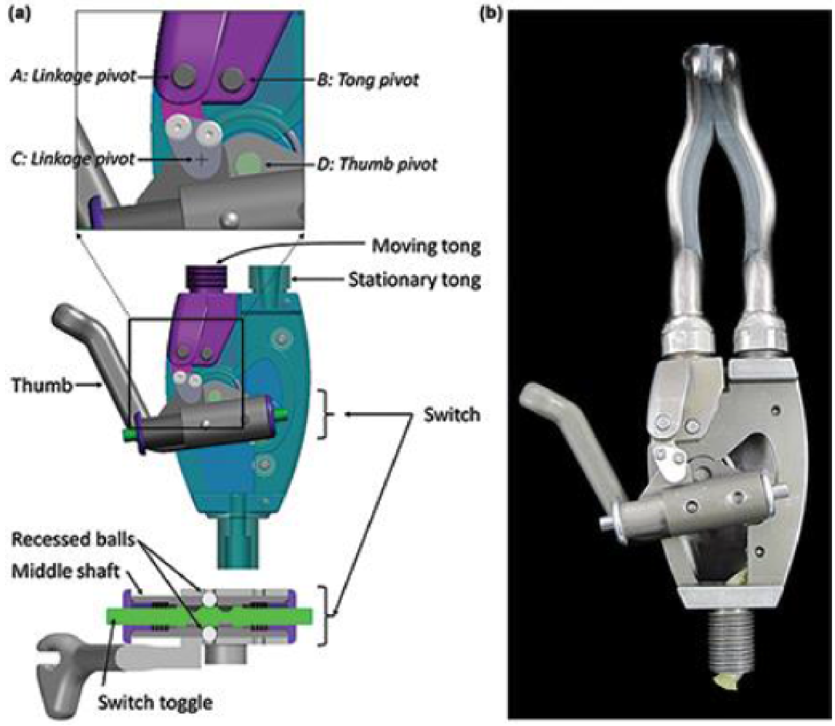

Figure 45: Working principle mode-alternating hook designed by Sensinger et al. (extracted from [38])

The prototype is based on the principle of linkage singularity [38], which is visualized in Figure 46.

When at least three joints are aligned, linkage singularity occurs (Figure 46 a)). This implies, force acting on the input joint does not lead to an unique movement. On the contrary, it can result into both: the output joint moving upwards or downwards.
When the third joint is shifted out of the line, movement direction is defined uniquely. With the third joint being above the line of singularity, force acting to the right will cause the last joint to move upwards. In contrast a force acting in the same direction will cause the last joint to move downwards, if it is initially positioned below the singulary state [38, 89].

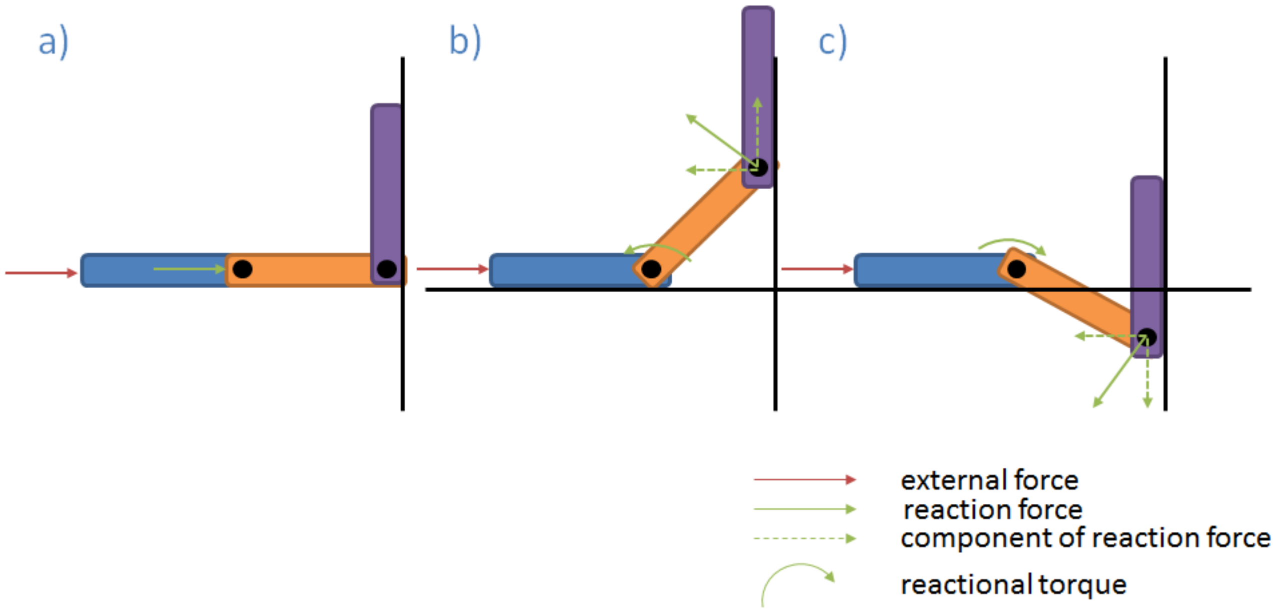

Figure 46: Illustration of a) linkage singularity and b) & c) uniquely defined movements (adapted from [89])

The VO/VC-device of Sensinger is based on this principle as can be seen in Figure 47 [38]. However, a toggle is needed to have the joint passing the singularity state [38, 89].

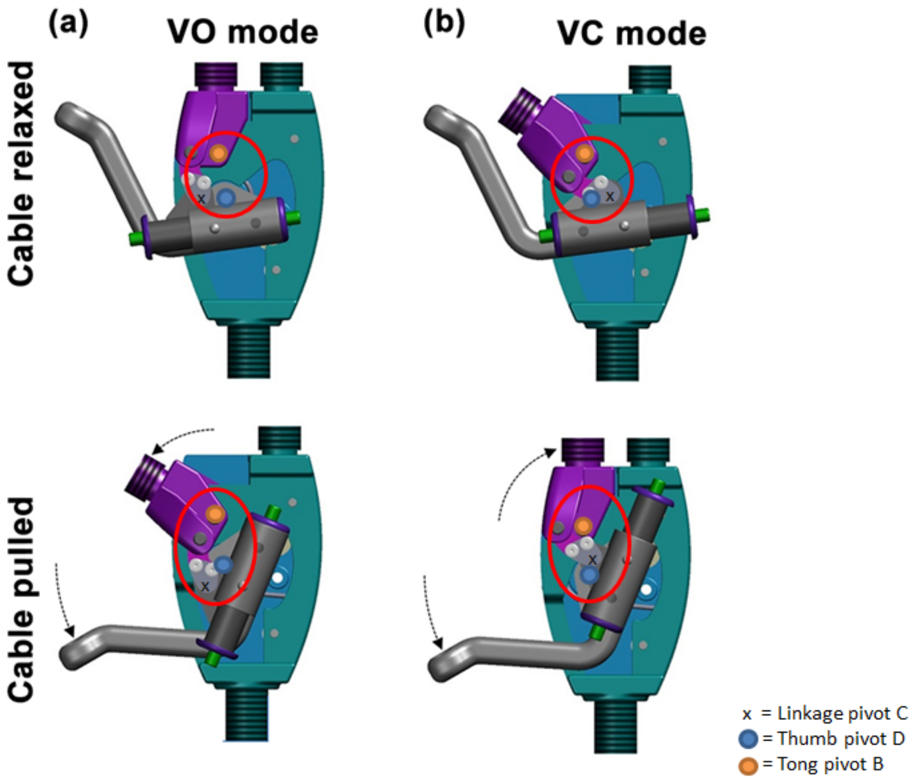

Figure 47: Working principle mode-alternating hook designed by Sensinger et al. (extracted from [38])

In this prototype, the relative position of linkage pivot **C** to thumb pivot **D** determines the operating mode of the device. If the linkage pivot **C** is positioned to the left of the thumb pivot **D**, the TD is in VO-mode. Consequently, the prehensor legs are closed in the default state. By tensioning the control cable the movable leg of the TD rotates around the tong pivot **B**. Consequently, the TD gets opened. The opening is conducted against a spring. As soon as the tension in the cable is stopped, the spring pulls the movable leg back into its default state.
By pressing the green switch toggle inwards and pushing the toggle to the right, the outer sliding cylinder is moved along the middle shaft. Hence, the linkage pivot **C** is shifted to the right of the thumb pivot **D**. At the same time, the movable leg is changed to its open position. Now the TD is in VC-mode. When the control cable is pulled, the movable leg conducts a clockwise rotation around tong pivot **B** causing the prehensor to close.
By pressing the green switching toggle and pushing the outer cylinder to the left side, the TD gets switched back into VO-mode [38, 89].
In Figure 48 the forces acting in VO- and VC-mode are shown.

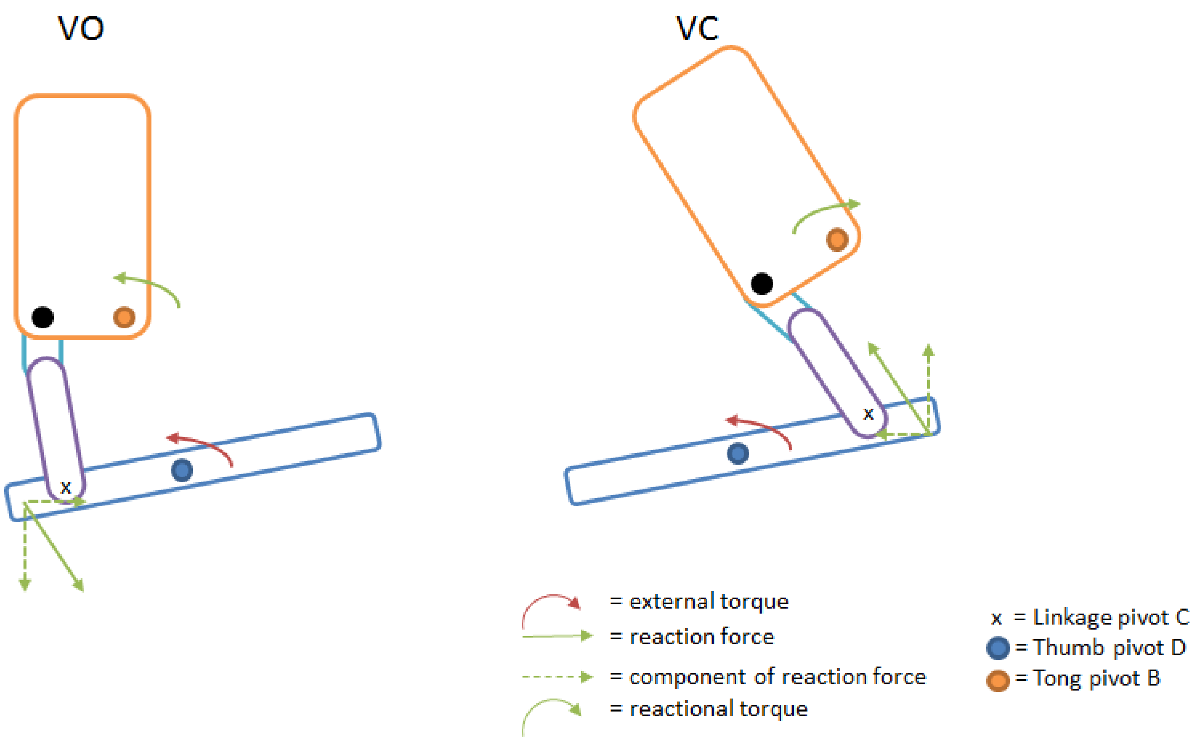

Figure 48: Forces acting in the mode-alternating hook designed by Sensinger et al. [38, 89] causing reversed rotational movements of the movable leg

It can be seen, that in both modes the direction of the initial torque coincides. However, in the VO-mode the torque causes the movable leg to rotate in counterclockwise direction. In contrast in the VC-mode it leads to a clockwise rotation of the movable TD leg. The different output directions though having the same input is caused by the different relative position of the linkage pivot **C** to the thumb pivot **D** in the different modes.

One additional patent was found, which describes a TD, whose mode can be changed by operating a toggle with the sound hand. However, in the patent *US 7,341,295* by Veatch & Scott [90] instead of changing the rotation direction of the movable leg, it is varied, which gripper leg is the movable one: in VO-mode the lower leg is movable and the upper one stationary; in VC-mode it is reversed as illustrated in Figure 49.

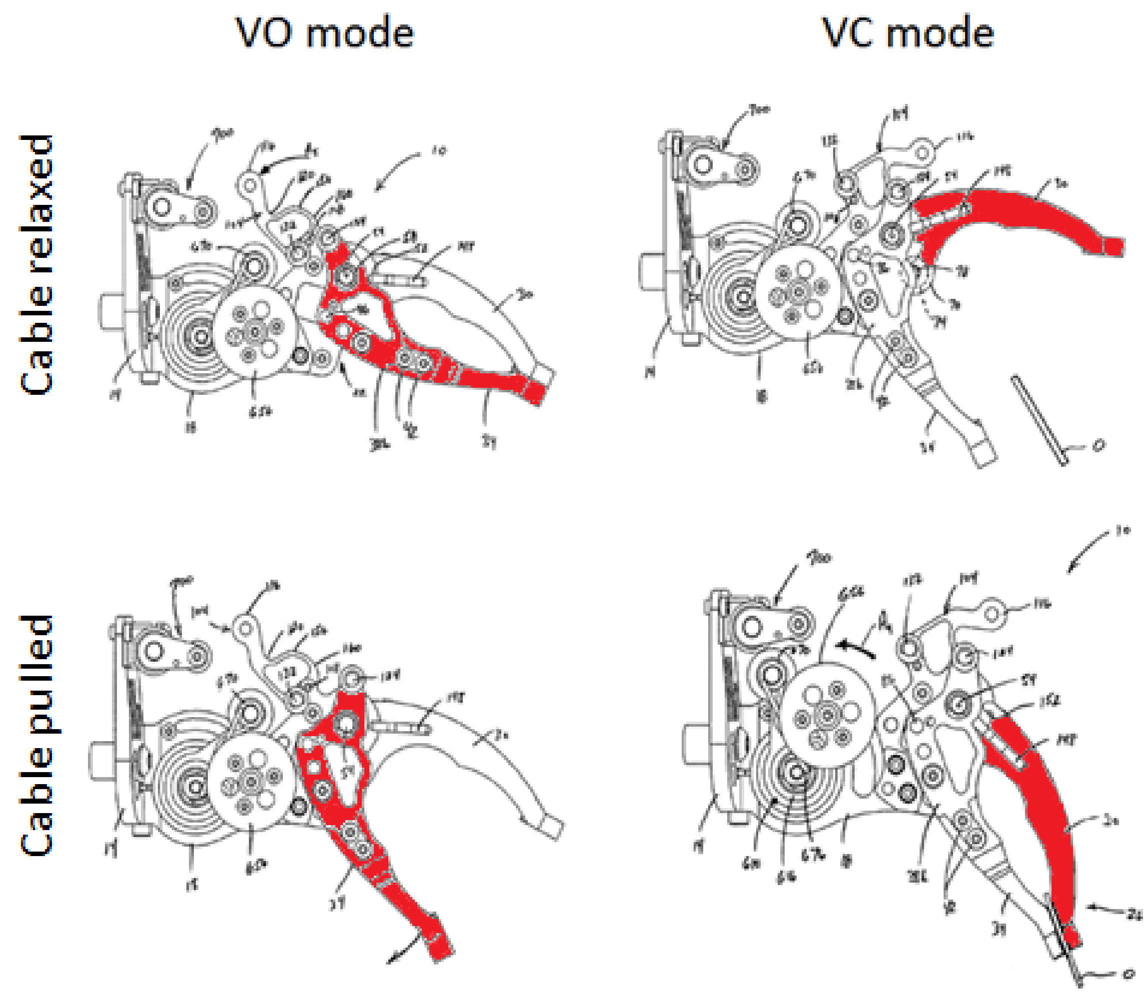

Figure 49: Veatch & Scott's mode-alternating terminal device (extracted from [90])

Both gripper legs **30** and **34** are mounted on the common shaft **54**. This shaft is rotated when the control cable **682** is manipulated [14]. The position of lever **104** determines, which leg will follow the rotational movement of the shaft **54**. When the lever **104** is positioned in its proximal position, bar **148** locks into the notch **152** preventing movement of the upper leg - the device is in VO-mode.
In contrast, having the lever **104** tilted to the front, the notch **120** of the lever **104** catches shaft **124** and thus, blocks movement of the lower leg - the device is in VC-mode.
In order to switch from VO-mode to VC-mode, the amputee needs to push lever **104** forward by means of his/her sound hand. In doing so, the inclined part **156** of lever **104** moves along the shaft **124** until the shaft **124** is moved into notch **120**. Thereby, the lower leg is pushed opened. Since the distance between the shafts **124** and **132** is increased, the ligament comprising the two shafts is getting stretched. hence, a pretension is created in the tendon. By position the lever in its proximal location, the TD is changed into VO-mode.

[14] The force transmission of the control cable **682** is generally more complex due to a brake assembly being incorporated in the prosthetic devices. With this brake assembly, the amputee is capable to adapt his gripping force while already holding an object. The description of this mechanism is beyond the scope of this literature review, which is why the concrete force transmission from the control cable to the shaft **54** will not be explained in more detail

4.3. Hybrid prostheses

M.P. Schoen and K.W. Scott have filed the patent *EP 2 865 356* regarding a prosthetic hand, which is operated by a combination of body-powered and myoelectric control.
The joints of the fingers for flexion consist of pulleys, which can either be driven electrically by motors or by tensioning cables, which run within the grooves of the pulleys. The myoelectric signals serve as the input signals for the motors. They are used to preposition the hand in a particular grasp. For example the amputee can control the carpometacarpal joint of the thumb by myoelectrical signals, thereby varying between opposition or reposition of the thumb.
However, the actual prehension movements are conducted in body-powered fashion. The amputee uses a defined body-movement such as shoulder shrugging to close the hand. The reversed body motion is used for hand opening [91].

5. Realization of prosthetic wrist

Physiologically the human wrist can be flexed and extended approximately in the range of 60°-0°-50° and deviated in radial and ulnar direction in the range of around 20°-0°-30° [14]. Additionally, the human hand can be moved to a pronated and supinated position in the range of about 85°- 0°- 90° [92]. These rotational movements are actually performed by the forearm. When rotating the hand from a supinated to pronated position the radius moves over the ulnar [51, 93]. However, in prosthetic devices pronational/supinational movements are generally assigned to the wrist replacement in order to ensure that all amputee independently of the stump length can be supplied with the same wrist device [14, 51].
In everyday life the frequency of conducting pronation/ supination or flexion/ extension exceed the deviational movements by far. Hence, prosthetic wrists often either support rotational movements (e.g. Hosmer's *Friction Wrist*), or flexion/extension (e.g. Otto Bock's *MyoWrist* or Hosmers *Sierra Wrist*) or both wrist movements (e.g. Otto Bock's *MovoWrist Flex*). However, there exist a few devices , which facilitate all three "wrist" motions. This is e.g. accomplished by Liberty Technology in its *OmniWrist* by using a ball-and-socket joint [93].
An important feature of the wrist units is the locking system, which ensures that the selected wrist alignment stays in place. Consequently, the lock needs to be released before the wrist alignment can be varied. Thus, prosthetic wrist movement generally consist of three phases: lock releasing, changing wrist alignment, position locking. Similar to prosthetic prehension these phases can be conducted passively by means of the sound hand or actively (body-powered or externally powered)[14]. However, in the wrist units an additional category of partially active prosthesis has to be added. In partially active prosthesis either wrist alignment or lock manipulation is conducted actively and the other one passively. Fully passive wrist units are still very common [15]. Even companies offering one of the most advanced myoelectric hands might only offer a passive wrist to it. Steeper e.g. offers to its *bebionic hand* a totally passively adjustable *Multi-Flex Wrist*. Using the sound hand the wrist can be rotated by 360° in both direction and locked in the neutral position, in a 30°-flexed or in a 30°-extended position [94].
Due to the modular way of prosthetic construction passive wrist units can generally be added to both: to a myoelectric as well as to a body-powered hand prosthesis.
Apart from the totally passive wrist units, there also exist a big variety of prosthetic wrists, which are somehow myoelectric or body-powered controlled. Therefore, only (at least partially) actively controlled wrists will be covered in the following.

5.1. Myoelectric prostheses

In myoelectric prostheses the rotational wrist movement is generally controlled actively and flexion/extension passively. The active myoelectric control of wrists is comparable to the control of multiple grasp patterns.
The *AXON Wrist* offered by Otto Bock is an example of a wrist for a myoelectric prosthesis, which has wrist rotation controlled actively and flexion/extension passively. The amputee can flex the *AXON Wrist* up to 75° and lock it in five different positions. Furthermore, extension is possible up to 45° with three different locking positions. The amputee can rotate the hand actively by 360° and keep it in 24 differ-

[15] All the wrist units stated above (Hosmer's *Friction Wrist*), Otto Bock's *MyoWrist*, Hosmers *Sierra Wrist*, Otto Bock's *MovoWrist Flex* and Liberty Technology's *OmniWrist*) require the sound hand to operate the lock as well as to change the wrist position

ent positions [36]. The *AXON Wrist* rotation has an electric actuator and is myoelectrically controlled. The two electrodes usually used to control prehension will also be responsible for wrist pronation and supination. The control of four different motions (opening/closing, pronation/supination) by two inputs can be conducted either by means of co-contraction or by using the "*Four Channel*"-design.

Co-contraction application

When wrist rotation is controlled by using co-contraction, the electrodes have to different modes: "*prehension mode*" and "*wrist mode*". In "*prehension mode*" one electrode is responsible for terminal device opening and the other one for closing. In "*wrist mode*" one electrode controls pronation and the other one supination. The amputee can switch between modes by co-contraction the antagonistic muscles.

"*Four Channel*"-design

In the "*Four Channel*"-design two single side electrodes are used to control in total four different motions: prehensor opening/closing and wrist pronation/supination [37]. As described in the previous paragraph each electrode is responsible for one movement of the prehension mode and one movement of the rotation mode. However, with the "*Four Channel*"- control the mode is selected depending on the speed and intensity the muscle gets tensioned [12, 14]. When the amputee slowly starts to tension his muscle, the prosthesis is kept in prehension mode. In contrast to this, a fast and intense muscle tension will change the prosthesis into rotational mode. The functional principle of the "*Four Channel*"-design is visualized in Figure 50.

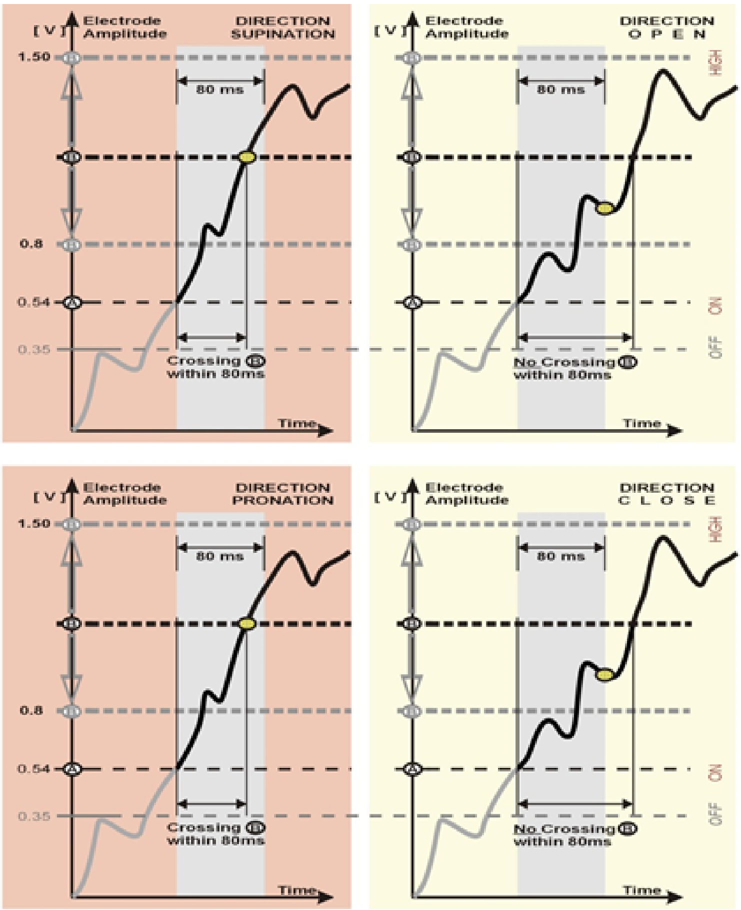

Figure 50: Signal intensity-time-graph illustrating the functional principle of the "*Four Channel*"-control (extracted from [95])

In the following an electrode is taken as an example, which is responsible for terminal device opening as well as wrist supination. As soon as the intensity of the recorded signal passes the "*On*"-threshold perception timing is activated. If the amputee contracts the muscle in such a way, that its signal intensity passes the second threshold within 80 ms, the device switches into the rotational mode and supination is initiated. As long as signal intensity is hold above the second threshold supination is conducted. If signal intensity drops blow this threshold, the device switches back to prehension mode. If the amputee contracts its muscle, but does not surpass the "*Four-Channel*"-threshold within 80 ms after reaching the "*On*"-threshold, the prosthesis will stay in prehension mode. Thus, the myoelectric signal controls terminal device opening proportionally.
Apart from Otto Bock's *AXONWrist*, e.g. the wrist designed by Zinck et al. [96] is controlled in a similar manner.

In myoelectric prosthesis often the implementation of an additional DoF leads to the additoin of an extra externally powered actuator. Apart from myoelectric signals, various mechanisms (e.g. mercury switch [97], controller node [29], magnetic sensors [98]) can be found in literature, which can be used to operate this actuator. However, these different control mechanism will not be elaborated further since they are not myoelectric.

5.2. Body-powered protheses

In early non-modular designs wrist movements were tried to be incoorporated into the body-powered prosthesis as well. In the *Arm of Charrière*, the more advanced arm of Pfister and the *Arm of Lange* and the *Hand of Fischer* pronation/supination and/or wrist flexion/extension were implemented, but they could solely be conducted in a passive way by means of the sound hand [46].
Eventually, prosthetic devices, which include body-powered controlled wrist movements, were developed. However, they need to be divided into partially active and fully active devices.
In partially active prosthesis either wrist alignment or lock manipulation is conducted actively and the other one passively. Consequently, either the lock of the wrist movement is freed by body-movements, but the sound hand or an assistant object is required for wrist alignment or prosthesis positioning is coupled to stump rotation, but the lock of the wirst is conducted by means of the sound hand [93].
In the following, different partially active wrists will be introduced. Following this, wrist devices will be introduced, which are controlled in a fully active manner.

5.2.1. Partially active wrists

In the following some partially active wrist devices will be introduced. They can be categorized depending on the wrist alignment or the lock operation being active.

Active wrist alignment

In rotational controlled prostheses, wrist rotation can be realized easily. Solely a switch has to be incorporated, by which stump rotation can either be coupled to TD prehension and or to wrist rotation. This idea was applied in the *Arm of Erlacher* or in the *Zawodnik-Arm* [46].
The *Carnes Hand* for below-elbow amputees also facilitates wrist flexion/extension and rotation. Since the pronation/supination-movement is controlled in a fully active manner, it will be described later on in Section 5.2.2. The hand is partially active with respect to its flexion movement. The amputee requires to unlock the wrist flexion by means of the sound hand. Once the flexion movement is free, an overloading force on the prehension control cables causes wrist alignment.

As illustrated in Figure 51 the distal hand portion is equipped with a pivoted circular arc segment **7**, which comprises three recesses **8**. The wrist flexion axis **9** passes through the center of this circular arc segment. At the inside of the arm shell a locking lever **10** is rotatably mounted. This locking lever **10** comprises a jut **11**, which can be wedged into one of the recesses **8** in the circular arc segment **7**. A spring **12** pushes the jut **11** of the locking lever **10**) into one of the recess, by what the wrist is locked into place. To unlock the wrist movement the amputee needs to move the locking lever **10** by means of the sound hand to the proximal position within the guide slot **13**. Consequently, the jut **11** cannot wedge into a recess **8** of the arc segment **7** freeing wrist flexion. Then, wrist flexion can be conducted by means of the control cables **3** and **4**, which are generally responsible for finger flexion and extension. When control cable **3** is tensioned, the finger flex. When cable **3** is fully unwinded and the finger are totally flexed or when the fingers experience a resistant movement so they can not be flexed further, an additional pull on cable **3** causes wrist flexion. On the contrary, the wrist conducts an extension movement, when cord **4** is fully unwinded and experiences an additional tension force. The wrist alignment can be secured, by moving the locking lever **10** back to the distal position of the guide slot **13** [51, 82, 83].

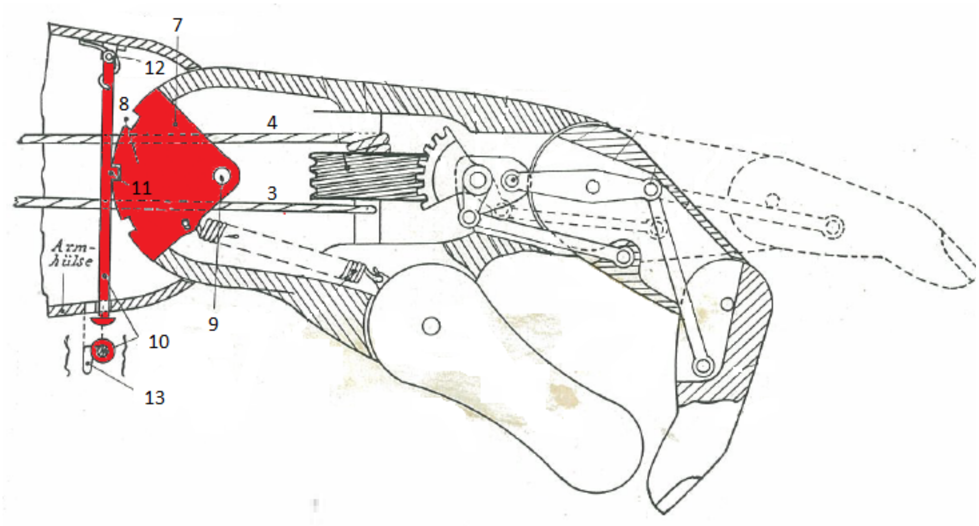

Figure 51: Wrist flexion of the *Carnes Arm* [83]

Active lock operation

The two commercially available, body-powered prosthetic wrists (the *N-abler* developed by Texas Assistive Devices and Hosmer's *4-Functional Wrist*) facilitate body-powered prosthesis users with rotational as well as flexional movements in the wrist. Wrist rotation is controlled partially active by having an additional control cable for wrist lock manipulation. In contrast wrist flexion is fully passive [93].

Hosmer's *4-Functional Wrist* (Figure 52) comprises a stationary base **1** and a rotatable upper part **2**. The upper part further consists of the TD attachment **3**, which can be tilted to facilitate device flexion/extension. To conduct wrist flexion, an the lever **4** needs to be pushed up by means of the sound hand. This retracts the flexion locking pin. Hence, the wrist can be flexed by applying a force e.g. by pressing the terminal device against the table. The wrist can be locked in three different flexed position. Wrist extension is accomplished the same way.

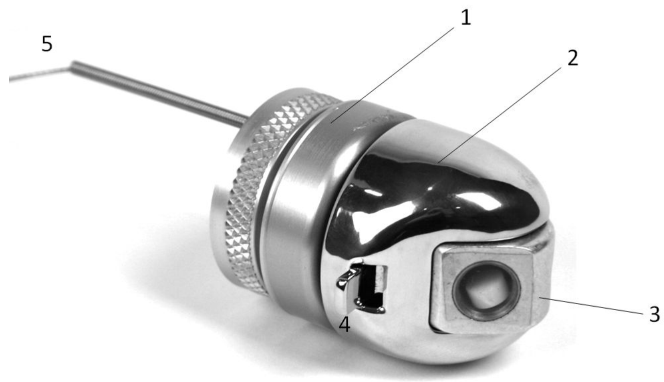

Figure 52: Hosmer's *4-Functional Wrist* [99]

In Hosmer's *4-Functional Wrist* there exists a control cable **5** to unlock the rotational movement. This cable is attached to the prosthetic harness, so the amputee can control the lock with a predefined body movement. To release the rotational lock the cable is first tensioned and then relaxed. After unlocking, the wrist can be pronated against a spring by means of the sound hand or with the help of another object. The wrist can be locked in 18 different rotated positions by pulling the rotation control cable once again. To supinate the wrist into its default state, the rotational lock needs to be released. Then the tensioned spring rotates the wrist back to its default state [99].

The *N-abler* (Figure 53) developed by Texas Assistive Devices is constructed and functions in a similar way. It comprises three parts: a static base **16**, with which it is attached to the prosthetic socket, rotational middle part**11** with the tiltable TD attachment **13**. The A-Version of the *N-abler* comprises two additional control cables: one is used to operate the lock of the wrist rotation **23** and the other one to control the wrist flexion lock **34**. Both cables are attached to the prosthetic harness.
In both cases, movement is unlocked by first pulling the corresponding control cable and then relaxing it. In this way, the corresponding locking pin is drawn back, allowing movements by means of the sound hand or another assistive object. The hand alignment is conducted against springs (flexion against a coil spring, pronation against a spiral spring). Consequently, by flexing or pronating the wrist the respective spring is tensioned. To keep the wrist in the desired position, the control cable needs to be operated again. In this way the locking pin is engaged again. When manipulating the control cable the next time, the locking pin is released and the energy stored in the spring drives the wrist back to its default state.
The wrist can be locked in 14 different positions of pronation and three different positions of flexion [100].

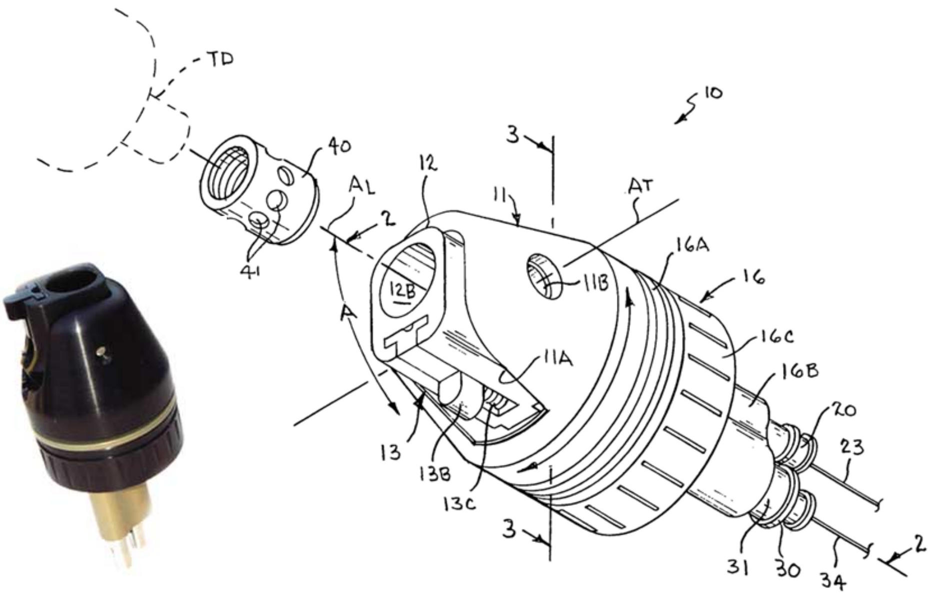

Figure 53: Texas Assistive Devices' *N-Abler* Version A (extracted from [100] & [101])

In the B-Version of the *N-abler*, wrist pronation is accomplished in a more active manner. The linear movement of a slider is transformed into rotational movements of the wrist: the more the amputee pulls the slider in proximal direction, the more the wrist pronates. This slider can be operated by pressing a nudge switch, which is positioned on the medial side of the prosthesis, against the body. Nevertheless, the sound hand needs to be used in order to flex the wrist [102].

5.2.2. Fully active wrists

In the following the devices will be described, which are controlled in a fully active way. Consequently, wrist lock as well as the alignment of the wrist is operated without the help of the sound hand. Depending on the fundamental principle of the active control, the devices can be categorized as "*requiring an additional control cable*", "*axillary control*", "*stump controlled*" or "*hybrid*". The mechanics of at least one device of each category will be depicted in the following.

Additional control cable

In literature some harness controlled prostheses can be found, which comprise in additional to the prehension control cable a second cable to operate wrist rotation atively. The *Arm of Béchard*, the first arm of Mathieu and the *Troendle Arm* are examples, in which prehension and wrist rotation are controlled by two different control cables and, thus different body-motions. When moving the forearm towards the body, wrist is supinated in the *Arm von Béchard*. Protraction and retraction of the shoulder leads to pronation and supination in the *Troendle Arm*[46]. No further information regarding the mechanism of the wrist or the locking mechanism of these devices could be found.

In the *Carnes Arm* the additional cable is used operate the wrist lock. As long as the lock is released wrist rotational is coupled to the flexion of the elbow. The rotational joint of the *Carnes Arm* is illustrated in Figure 54.

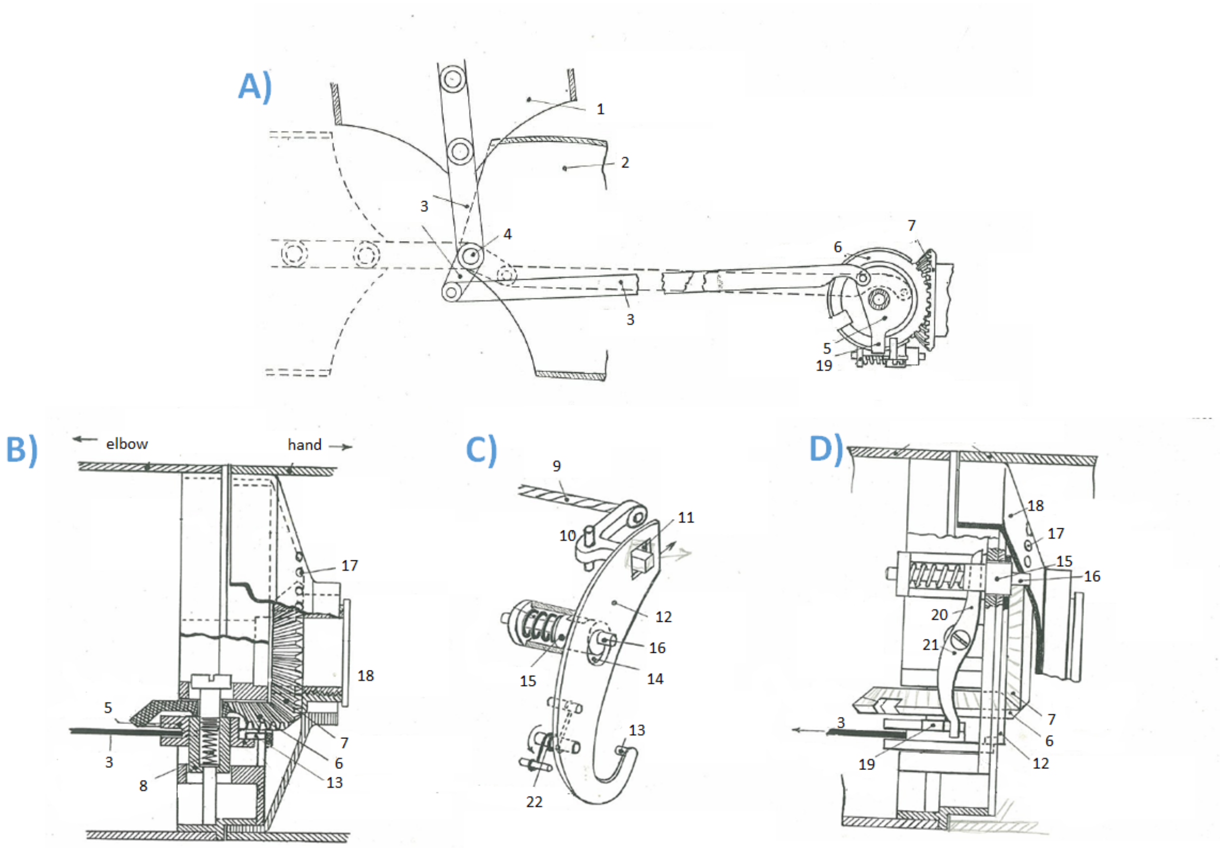

Figure 54: Wrist Rotation of the *Carnes Arm* [83]

The socket of the *Carnes Arm* consists of two parts: an arm cuff **1** and a lower socket **2**. The cuff **1** is worn around the upper arm and attaches the prosthesis to the amputee's body firmly. The lower socket **2** surrounds the stump and has the prosthetic hand attached. Furthermore, it comprises the

prosthetic wrist rotation mechanism.
The arm cuff **1** and the lower socket **2** are linked by rods **3** with a hinge **4** positioned over the elbow joint. The proximal part of the rod connection **3** is fixed to the arm cuff **1**. A driving disk **5** is attached to the other rod end **3**, which can selectively be coupled to the bevel gear system **6** & **7**. The rotational wrist part with the TD **18** is mounted to the bevel gear system **6** & **7**. Thus, motion of the bevel gears **6** & **7** is transferred to the rotational wrist part.
When the elbow gets flexed, the rod **3** attached to the driving disk **5** is moved in proximal direction. Hence, it initiates the driving disk **5** to rotate counterclockwise. In the case of the wrist lock being freed, the driving disk **5** is coupled to bevel gear **6** and thus, drags it along. Bevel gear **6** then again drives the engaging bevel gear **7** and consequently, the prosthetic hand to pronate. The other way around, elbow extension pushes the rod **3** in distal direction leading to the driving disk **5** moving clockwise, which causes the prosthetic hand to supinate.
In order to lock the rotational motion, the driving disk**5** needs to be removed from bevel gear **6**. This is conducted against a force of the spring **8**, which generally pushes the driving disk into connection with bevel gear **6**. Control cable **9** needs to be pulled to initiate decoupling of the driving disk **5** and the bevel gear **6**.
The control cable **9** is attached to a rectangular, pivoted lever **10**, which interlocks in a window **11** of a sickle-shaped lever **12**. At the tip of the sickle-shaped lever **12** a lug **13** is mounted, which can move the driving disk **5** out of its engagement to bevel gear **6**.
When the control cable **9** is pulled, it causes the rectangular lever **10** to rotate counterclockwise. Thereby, it pushes against the edge of the window **11** and causes the sickle-shaped lever **12** to rotate clockwise. Consequently, the lug **13** drags the driving disk **5** out of its default position.
During the clockwise rotation of the sickle-shaped lever **10**, a bore **14** in the sickle-shaped lever **12** gets pivoted in such a way, that it coincide with a bolt **15** of the same diameter. Hence, the spring-loaded bolt **15** can pass the sickle-shaped lever **12**. Then the trunnion **16** at the front of the bolt **15**, wedges into a hole **16** of the rotatable wrist part **18** causing the wrist alignment to be locked.
In order to release the locked wrist rotation, the elbow needs to be flexed as much as possible. In so doing, the projection **19** of the driving disk **5**, which is normally interlocked with bevel gear **8**, pushes against the arm **20** of a two-armed lever. The other arm **21** interlocks in a slot of the locking bolt. When the projection **19** of the driving disc **5** pushes lever arm **21**, lever arm **20** is moved in proximal direction dragging the locking trunnion **16** and the bolt **15** along. Due to the bolt **15** leaving the bore **14**, a spring **22** can rotate the sickle-shaped lever **12** to its default position. Consequently, the driving disc **5** is released and is able to contact bevel gear **6** again.
When the elbow is extended the following time, the projection **19** of the driving disc **5** can interlock with the corresponding notch in bevel gear **6**. Finally, the coupling of elbow flexion and wrist rotation is fully restored [83].

G.M. Motis has patented a prosthetic wrist, which also requires an additional control cable. However, this time the linear cable motion is actually transformed by a pulley system into wrist rotation. Consequently, wrist rotation is independent of the elbow motion. As soon as the tension in the wrist control cable is released, wrist rotation is locked. Pronation and supination are controlled with the same cable. The direction of the rotational movement is sequentially switched by means of an alternator after each operation cylce. [103].
The concrete mechanism of G.M. Motis Patent *US 3,466,937* is illustrated in Figure 55.

The vertically oriented idler pulleys **24a** and **24b** span together with the horizontally oriented idler pulley **35** the driving cable **50**. This driving cable **50** also runs over the main pulley **13**, on which it is fixed by the screw **55**. Depending on the direction the driving cable **50** is pulled in, the main pulley **13** rotates clockwise or counterclockwise. The terminal device **11** is attached to the main pulley **13**. Thus, it follows the rotation of it.
The pull direction (clockwise or counterclockwise) of the driving cable **50** is changed by means of the alternator **115** after each operation cycle. The control cable **100** of the harness is attached to this alternator **115**. When the amputee tensions the cable, the actuator **115** is pulled in proximal direction. The alternator **115** comprises a pawl **110**, which hooks alternating into slider **60a** or slider **60b**. Consequently, the alternator drags the slider along, to which he is linked to, and thereby determining

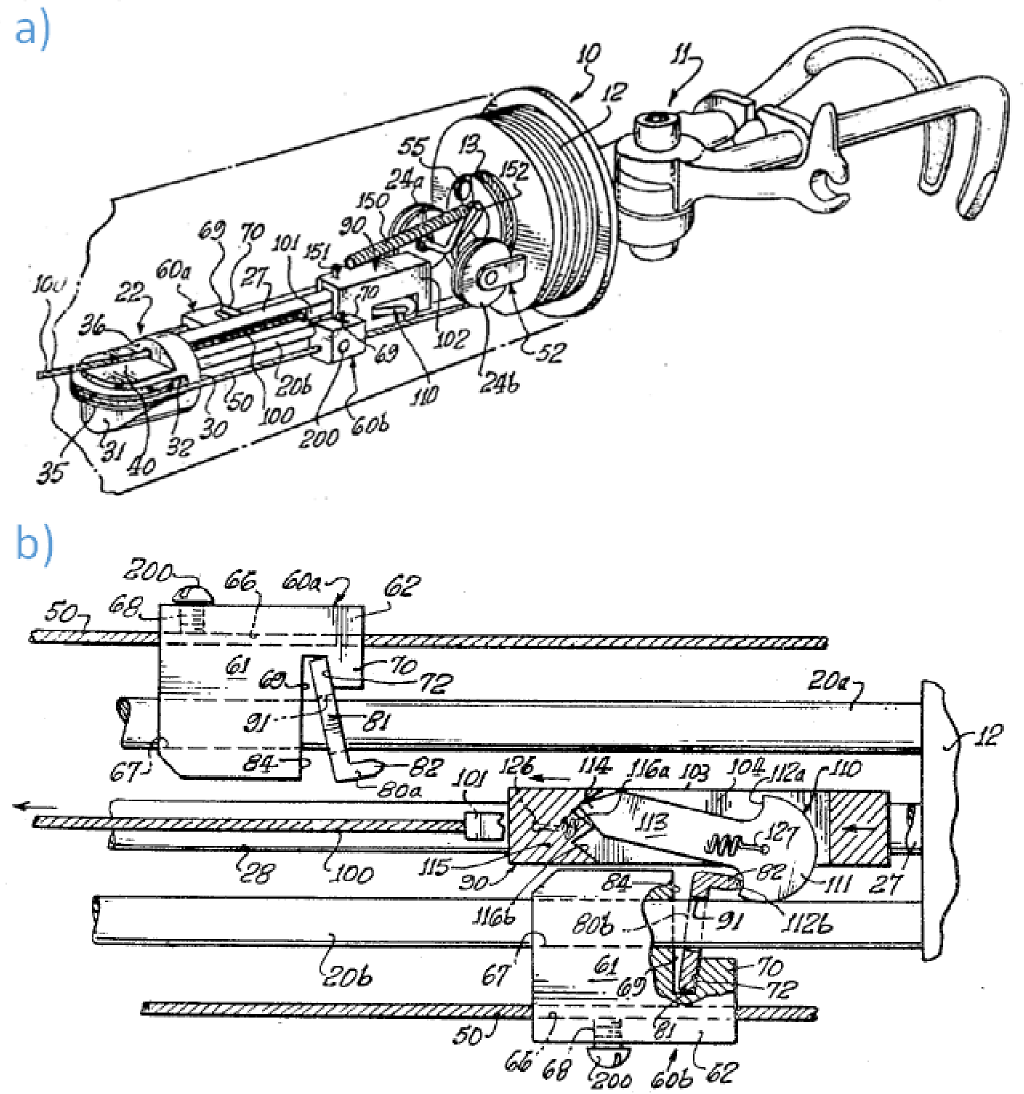

Figure 55: Mechanism of the "*Linear to Rotational Movement Converter*" [103]

the direction of the driving cable **50**. The driving cable rotates clockwise, if slider **60b** is pushed along. In contrast it is pulled counterclockwise, if slider **60a** is moved. Each time the amputee releases the control cable tension, the alternator **115** is pulled back to its default state by means of spring **125**. Additionally, the tilt of the pawl **110** is changed, so it will hook into the other slider next time the control cable **100** will be tensioned [103].

Axillary Control

Axillary control describes a control button being located within the amputee's arm pit. The amputee can exert force on the button by adducting his/her arm. The button application is used to switch the operation mode of the control cable. When the button is released, the amputee can open or close the prosthetic hand by operating the control cable. Having pushed the button in, the control cable is coupled to the wrist rotation instead.
One example of the axillary control is the *gear drive* of *Northrop Aircraft, INC.* as shown in Figure 56.

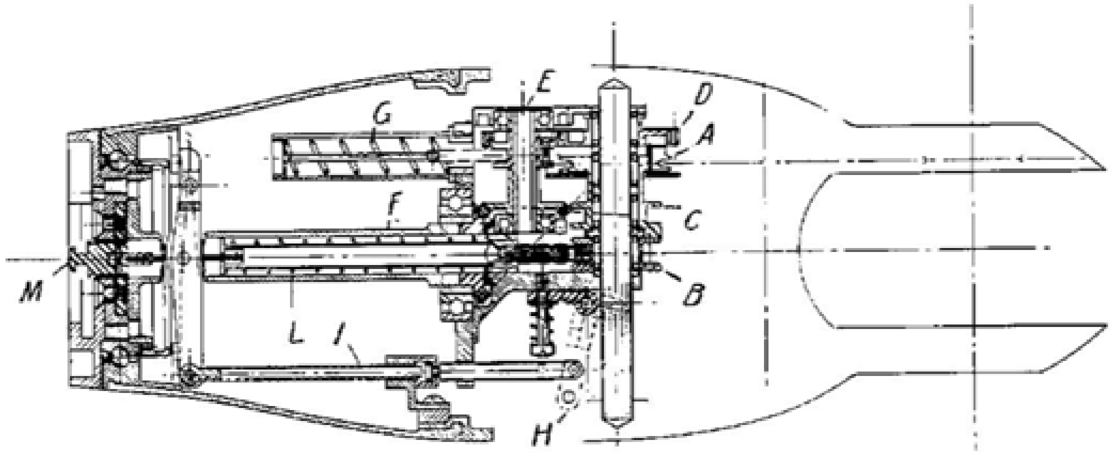

Figure 56: Axillary controlled *Northrop Aircraft, INC.*'s *gear drive* (extracted from[65])

The control cable is attached to pulley **A**. When the axillary control button is released, pulley **A** is coupled to pulley **C** by a key way system. Tension applied to the control cable in this configuration leads to pulley **C** following the clockwise rotation of pulley **A**. Thereby, pulley **C** drives the pulley **B** in the same direction. A moving platform with the hook attachment **M** is linked to pulley **B**. The clockwise rotation of the pulley **B** causes the moving platform to move in proximal direction and hence, leads to TD opening. At this, the moving platform preloads the compressing spring **L**. As soon as the control cable force is released, the return spring **L** expands and thereby, bringing the TD back to its closed position.
The axillary control button is attached to lever **H** in such a way, that button operation leads to lever **H** being pulled in proximal direction. Shaft **I** is linked to lever **H** and hence, gets pushed along. Thereby the system blocking the rotation system is released. At the same time the shaft, on which pulley **C** and **A** is fixed on, is pushed upwards by lever **H**. Hence, pulley **C** gets disconnected from pulley **B**. Consequently, no power can be transmitted to the sliding platform and the hook anymore, instead pulley **A** is coupled to gear **D**. Gear **D** intersects a gear positioned on shaft **E**, whereby it drives the rotation of the shaft **E** with its attached bevel gear. The bevel gear in turn moves the shaft **F**, which causes the hook to rotate.
When the axillary control button is released, springs will shift the system back to its original configuration with pulley **C** coupled to pulley **B** and wrist rotation being locked.

Stump controlled

Northrop Aircraft, INC. have described in their *Final Report on artificial arm and leg research and development* [65] a big variety of devices, which facilitate wrist pronation/supination controlled by remaining stump rotation. In some designs a step-up mechanism is included to increase the ratio of stump to TD rotational movement.
In general the different devices are controlled in a comparable way and they solely vary regarding their concrete mechanics. Hence, only two designs will be explained in more detailed, for which patents have been granted.
Northrop Aircraft's *Gear Drive With Roller Lock* is patented in US 2,457,316. The patent describes a stump controlled prosthetic wrist, which locks automatically, when control torque is released or torque arises from the hook [65, 104]. The mechanism is shown in Figure 57.

The prosthetic socket comprises an outer shell **23**, an inner shell **14** and a stump socket **15** connected to the latter. The outer shell **23** is firmly attached to an arm cuff on the amputee's upper arm and hence, fixates the prosthesis. A housing **11**, to which the TD is attached to, is slid in the distal end of the outer shell **23**. In the inside of the outer shell **23** the housing **11** is connected to the inner shell 14

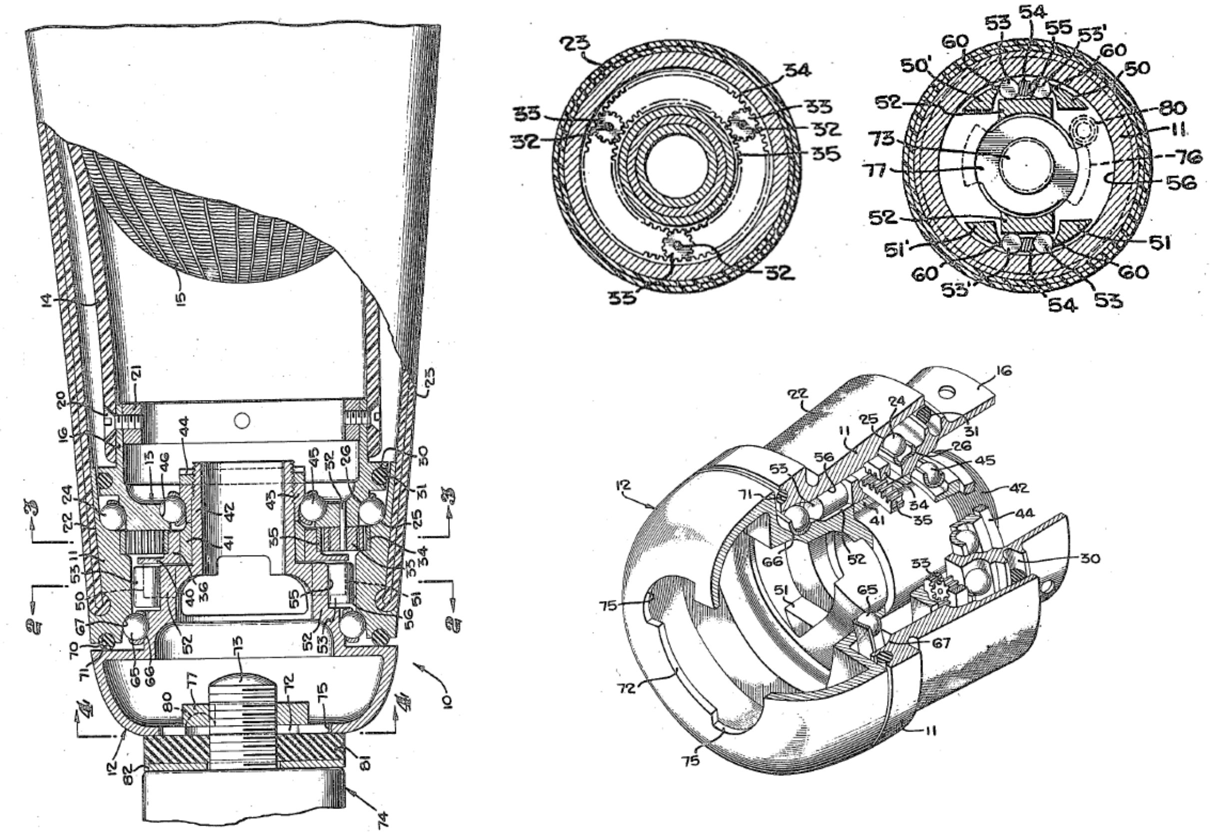

Figure 57: Stump controlled wrist movement with roller lock [104]

and hence, coupled to the stump socket **15**. The stump socket **15**, the inner shell **14** and the housing **11** can rotate relatively to the outer socket **15**. Consequently, rotational movement of the amputee's stump leads to pronation/supination of the TD. However, the described device comprises a planetary gear system to increase the ratio of stump to TD rotation.

For this, the housing **11** consist of two parts: a proximal part fixed to the inner shell **14** and a distal cap **12** connected with the TD attachment **13**, which lies within the fixed part. A sun gear **32** is coupled to the TD attachment **13**. Planetary gears **33** surround the sun gear **13** and are in contact with gear racks embedded within the fixed housing part. Consequently, stump rotation is transferred to the planetary gears. These in turn drive the sun gear and thus, the TD. Due to this planetary system, the cap will rotate 2.3 the amount of the stump socket **15**. When the amputee stops stump rotation, the wrist will keep its current alignment.

An additional feature of the device is to solely transmit torque from the stump to the TD and not vice versa. This is accomplished by a freewheel mechanism: Two sets of balls **53** and **53′** are positioned between part **52** of cap **12** and the inside surface **56** of the fixed housing part. A spring **54** connects the two balls of one set. Lateral motion of the balls is restricted by the wedges **50** and **50′**.

When a relative motion between part **52** and housing **11** occurs, the spring-connected balls are getting pushed together. Thereby, they are getting wedged between the surfaces and thus, preventing further relative motion.

However, wrist rotation is desired, when initiated by stump rotation. When bushing **40** rotates relatively to the pinion attachment **13**, it pushes the the wedges **50** & **50′** between the balls **53** & **53′** and the housing inside. Consequently, the cap **12** is free to follow the rotation of the sun gear **35**. As soon as the stump motion stops, the bushing **40** does not push against the wedges **50** & **50′** anymore. Then the springs **54** force their balls **53** ´& **53′** back to their original configuration and hence, lock the wrist motion.

An advancement of the design described in *Norhtrop Aircraft INC.*'s *Final Report on artificial arm and leg research and development* as the *Reaction lock, cable drive*-wrist [65] is depicted in the US Patent 2,638,604 [105] by G. M. Motis. The patent comprises a prosthetic device, in which wrist rotation is also controlled by stump rotation. Furthermore, it has a lock incoorporated, which automatically blocks wrist movement, when the prehension control cable is tensioned [105].
The design is illustrated in Figure 58.

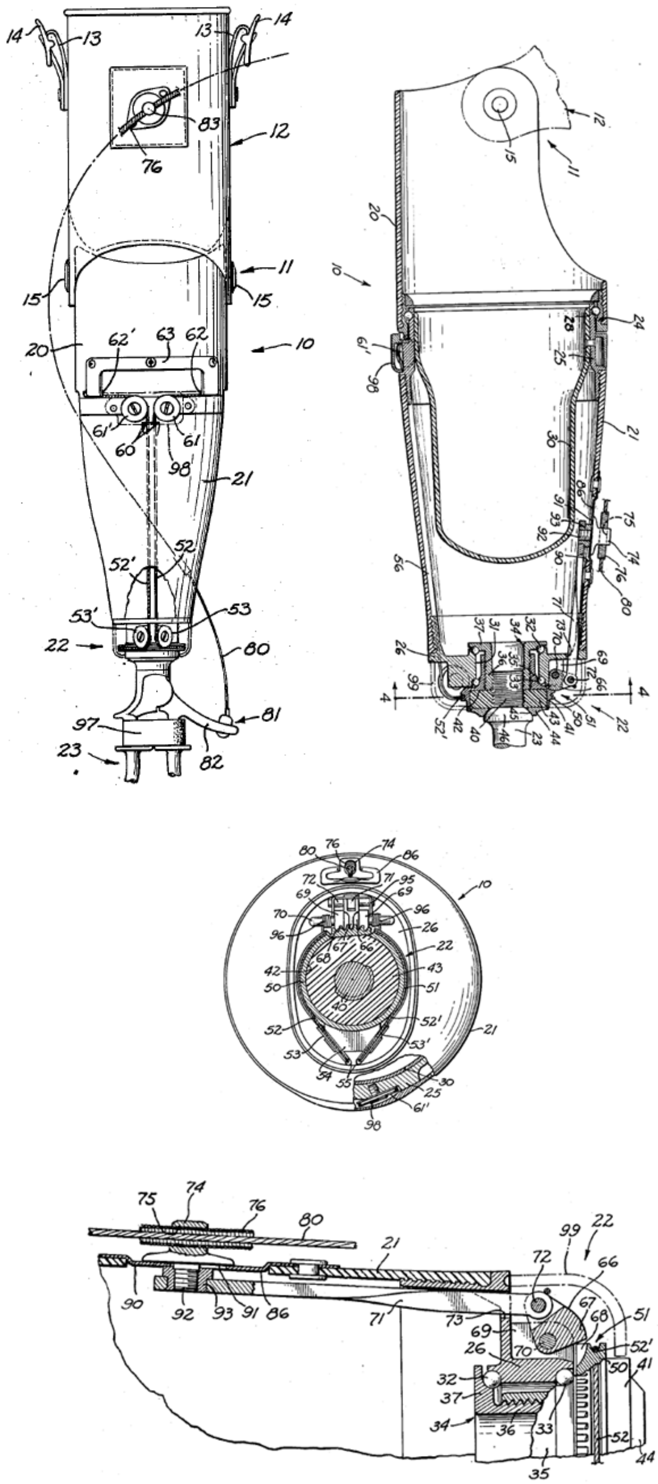

Figure 58: Stump controlled wrist movement with automatic lock [105]

This design comprises two shells: a fixed one **20** and a rotatable one **21**. The fixed shell **20** is connected to a cuff positioned on the amputee's upper arm. The movable shell **21** comprises a stump socket **30** and is rotatable attached to the fixed one **20**. A cap **22**, to which the TD is mounted to, is rotatably positioned on the distal end of the movable shell **21**. In this prosthesis a step-up mechanism is based on two pair of pulleys **53** & **53'** and **61** & **61'**. The pulleys **53** & **53'** are positioned within the cap **22**. The other pair **61** & **61'** is located at the distal end of the movable shell **21**. Over each opposing pulley set **53** & **61** and **53'** & **61'** a cord **52** & **52'** respectively spans. One end of the cords is attached to the cap **22**. After passing the pulleys **61** & **61'** the cord is wrapped around the arm and fixed to the stationary shell **20**. Due to the difference in the diameter of the parts, to which the cord ends are attached to, the movement of the stump is doubled for the cap **22** movement.
In this device wrist motion is blocked as soon as the prehension control cable **80** is pulled. For this an operator **74** is attached to the control cable housing **76** and is positioned within a slot **90** in shell **21**. On its other side the operator **74** is connected to a lever **71** with a pivoted wedge **66**. The wedge comprises a cam **67**, which can lock into the toothed portion **68** of the TD mounting **35** inside cap **22**. Hence, it can block relative rotation between the cap **22** and the outer shell **21**.
The control cable stretches from the distal, anterior operator **74**, to the proximal, posterior fitting **83** and finally to the control harness. When control cable **80** is pulled, it tends to straighten out. Because of the cable housing **76** being firmly attached to the fitting **83** and to the movable operator **74**, the cable housing **76** can solely straighten out by pushing the operator **74** in distal direction. Hereby, lever **71** is dragged along causing its wedge **66** to rotate clockwise and position the cam **67** into the toothed portion **68**. Consequently, the wrist movement is locked. When the tension on the prehension control cable is released, wedge **66** is forced to rotate counterclockwise to its default position by means of the torsion springs **96**. Hence, the lever **71** and the operator **74** are moved back its default state thus releasing the wrist lock [105].

5.3. Hybrid prostheses

Stobbe et al. [106] state having facilitated a body-powered prosthesis with wrist movement by using myoelectrical signals. The myoelectric control is solely used operate the wrist lock. The movement of the wrist is supposed to continue to be body-powered [106]. Unfortunately, no details of the actual mechanism of the device could be found.

6. Current research to achieve multiple degrees of freedom

The challenge of replacing the human upper extremities lies in acquiring sufficient inputs, which can control the high number of DoF. Input sources are restricted in current myoelectric and body-powered control. A lot of research has been conducted to actually increase the number of control inputs or to be able to interpret the currently obtainable once in such a way, that they can be used to drive multiple joints. Especially in the field of myoelectric prosthesis numerous advancements of the control mechanism can be found. However, a few studies have also been performed to increase input sources for body-powered prosthesis. Both will be introduced shortly in the following.

6.1. Myoelectric prostheses

The signals recorded by surface electrodes are disturbed by the tissue layers, they need to pass, signals from adjacent tissue like other muscles and other external artifacts. Hence, the surface electrodes generally record the superposition of multiple signals. To ensure distinct signals for prosthesis control, solely two electrodes can be used. In the field of myoelectric control current research either focus on how the signals of the standard two electrodes can be interpreted in a specific way or how the actual number of control inputs can be increased and applied. Research of both categories will be presented in the following.

6.1.1. Interpretation of the signals recorded by two electrodes

Schulz et al. [52] expressed the idea to program control commands based on the idea of the Morse code. For this each particular grasp type will have a predefined control allocated. The control sequence can comprise short trigger signals or long lasting ones. The length of the control sequence depends on

No.	Order	Code	Function
1	T	–	Neutral hand position
2	E	●	Rotate thumb
3	M	– –	Index finger
4	N	– ●	Hook grip
5	A	● –	Lateral grip
6	I	● ●	Three-point grip
7	O	– – –	Pincer grip
8	G	– – ●	Close thumb
9	K	– ● –	Hold writing instrument
10	D	– ● ●	Hold fork
11	W	● – –	Hold knife
12	R	● – ●	Hold spoon
13	U	● ● –	Hold toothbrush
14	S	● ● ●	Reset to neutral position

Figure 59: Possible control sequences and corresponding grip pattern with - = long muscle signal and • = impulse signal (extracted from[52])

how often the particular grip pattern is used in activities of daily live [52]. An example of the prosthetic Morse code is displayed in Figure 59.

6.1.2. Increased number of control inputs

Body movements are combinations of multiple muscle activities. It is known that for each body movement a characteristic myoelectric pattern can be recorded from interacting muscles. One advancement of myoelectric control is pattern recognition, in which these characteristic signal patterns are used to control prosthesis movement.Therefore, myoelectric signals of multiple, active upper limb muscles are recorded. A microprocessor analyzes the collected data and translates the signal pattern into the limb movement, the amputee possibly tended to conduct. According to this, it stimulates the actuators necessary to conduct the desired arm movement. Recently, Coapt Engineering brought the first prosthesis controlled by pattern recognition on the market [15, 53, 107].

Another way how to reduce the artifacts recorded from surface electrodes are electrodes, which are directly implanted into a muscle. Thus, these intra-muscular electrodes are shield from the activities of adjacent muscles and solely record the activity of the muscle it engages. Consequently, electrodes can be implanted into adjacent muscles, by what the number of electrodes can be increased. Thru a magnetic field the electrodes can receive its energy from an externally worn power source. The same way, the electrodes are able to communicate the recorded signals to the prosthesis [108–110].

Targeted-muscle reinnervation (TMR) is an other, very invasive advancement of the myoelectric control. Due to limb amputation nerve strings loose the muscles it physiologically controls. In addition, muscles remain without functional value, because the joints, whose movement the muscles physiologically supportare removed. Consequently, in a stump there exist redundant nerve endings and muscles, which could generally be functional. By reinnervating these redundant nerve strings into the muscles a new way of prothetic control is accomplished. The new reinnvervated nerve strings will now direct the motor command for the intended arm movement to the newly innervated muscles. The contraction of these are recorded and used to control a prosthesis function. TMR is especially beneficial for patients with higher limb amputations e.g. shoulder disarticulation. These patients need to receive a the highest number of joint replacements, but they do not provide sufficient control sources. By splitting the redundant pectoral muscles up and reinnervating it with multiple nerv strings, multiple control sources can be created. More recently, TMR was tested for above-elbow amputees. Here, parts of the biceps and parts of triceps muscle are innervated [15, 111, 112].

6.2. Body-powered prostheses

Apart from new hand prosthesis mechanisms, researchers promote body-powered prosthesis with multiple degrees of freedom by investigating other potential control motions. They are aiming to adapt the currently common harness design to facilitate more than one control cable. However, it needs to be ensured that the multiple cables are operated by distinctly different body motions.
In the old prostheses designs with multiple control cables, it was very challenging for the amputee to tension solely one cable at a time without effecting the other one. This needs to be prevented.
A. N. Vardy & D. H. Plettenburg for example have measured the relative displacements on defined points on the shoulder during its motion. They state, that for prosthesis, which require small cable force due to pneumatic, hydraulic or electrical assistance, locations on the ipsilateral shoulder can be found. When the prehension can be controlled by the ipsilateral shoulder, the contralateral shoulder can be used for an additional degree of freedom e.g. wrist rotation [113].
E. H. A. van Mil examined in her Master thesis [114] not regularly used body motions (e.g. shoulder elevation, lateral trunk flexion, toe flexion), which could serve as control sources for VO/VC-devices. Even though she had tested multiple movements, she revealed the currently used motions of the shoulder being most suitable for purely mechanical body-powered prosthesis control. In order to achieve a two-way controlled prosthesis, she recommends to use each shoulder for one prehension direction. She generally also suggests to extend the body-powered mechanical hands by pneumtic, hydraulic or electrical assistance [114].

7. Discussion & Conclusion

The two main control mechanisms of commercially available hand prostheses have both specific advantages and disadvantages. Myoelectric prostheses for example have the special characteristic of facilitating multiple degrees of freedom (DoFs), which means in this review, that they either promote the thumb to be switchable between a lateral and an opposed position, varying which finger contribute to the grasp and thereby allowing the user to select from different grasp types (e.g. pinch grasp and power grasp) or wrist movements. Body-powered prostheses on the other hand provide the feature of extended proprioreceptive feedback. Hence, the user knows the status (open or closed), motion and position of his/her prosthesis without visually tracking the device. Both features are highly advantageous for the patient, because they either reduce the physical or the mental load. Various attempts have recently been made to implement proprioreceptive feedback into myoelectric prostheses. However, so far the task remains a challenge and has not yet been achieved in an intuitive way. Ergo, it might be more practical to add the feature of multiple DoFs to body-powered prostheses [16]. Based on this idea the previously presented literature review served to investigate, if attempts have already been made to endow body-powered hand prostheses with additional degrees of freedom and if so, why they have not been successful until today. Furthermore, it was studied, if engineers are currently working on this issue and how they are trying to implement it.

From a very extensive literature review with more than 540 titles considered 67 different records (papers, books, patents) were concretely elaborated on in this review. These records described various attempts of body-powered devices with multiple DoFs. Since in this review, a device is said to facilitate multiple DoFs, if it either enables different grasp modes or if it supports wrist motions, the findings could be categorized with respect to these two types of implementing multiple DoFs. Even though the concrete mechanic of the additional DoF varies among the devices, it was noticeable, that the control of the new feature was realized in similar ways. For example the majority of the devices in both categories either used an additional control cable or required the sound hand to realize a new DoF. These ways of implementations represent both a major subgroup in the two main categories (multigrasp hands or wrist components), when sorting the found devices based on the resemblance in the control mechanism. Other ways of implementing different grasp modi in the category of multigrasp

[16] In this literature review, it is focused on purely mechanical body-powered hand prostheses and hence, leaving out body-powered prostheses with pneumatic or hydraulic assistance to narrow the number of devices.

hands are: having a defined closing trajectory, a distinct thumb alignment, a default and secondary grasp or by means of underactuation. Moreover, the literature research regarding multigrasp prostheses also led to the special prosthetic type of VO/VC-devices, which were also addressed in this review. In commercially available, body-powered prostheses the prehension motion can solely be controlled actively in one way (opening or closing). The reversed motion is conducted by means of passive elements like springs or elastics. Depending on the prehension mode (opening or closing), the user can operate voluntarily, the prosthesis is classified as voluntary-opening (VO) or voluntary-closing (VC). Researchers have been trying to design prostheses, which can be alternated between a VO- and a VC-mode and hence, facilitate a two-way control. Even though they technically do not increase the number of DoF neither regarding the engineering definition of "*DoF*" nor following the definition given in this literature review, VO/VC-devices are approached in Subsection 4.2.2. The author decided to incorporate this type of prostheses, because they illustrate an important step towards multiple DoFs: The two-way control allows the patient to voluntarily operate hand opening as well as hand closing. Hence, it includes an extra active operable motion to the prosthesis and consequently bestows more control power and awareness to the user - two features the addition of multiple DoFs aims at. Since the two-way control is generally realized by some kind of switching mechanism, VO/VC-devices illustrate possibilities how different operation modes can be selected. Despite VO/VC-devices demonstrating major steps with regard to multiple DoF, it has to be emphasized, that they do not present actual solutions to the research questions. Therefore, their functionality will not be discussed any further.

In the category of prosthetic wrist components another division needs to be conducted before focusing on the actual control mechanism. A prosthetic wrist component consists of two parts: the mechanism for wrist alignment and a locking mechanism to keep the wrist in place. In some devices solely one mechanism can be controlled actively without the help of the sound hand. Hence, the wrist components are classified as fully active or partially active devices. Both categories can be subdivided with respect to the concrete control mechanic of the two operable parts: e.g. requiring additional cables, based on overloading principle, using axillary or stump control.

All devices found in the scope of this literature review[17] are summarized in Table 1 and supplemented by a short description of its special features, the category/ies it is allocated to and its time of origin.

[17] The VO/VC-devices are left out of this overview since they strictly do not present actual solutions to the research questions. A summary of all VO/VC-devices depicted in this literature review can be found in Appendix B

Table 1: Overview of all devices found within the scope of this literature review

Device	Features	Category	Year	Pages	
Hand of Ballif	Two different control cables: one for fingers and an individual one for the thumb (intended, but not successful)	Multigrasp → Two control cables	1812	24-25	[46]
Hand of Eichler	Able to conduct pinch as well as power grasp	Multigrasp → Two control cables	1836	26	[46]
Tureman Hand (US 2,435,614)	Control of individual finger / finger combinations	Multigrasp → Multiple control cables	1945	26-28	[61]
Troschinski-Arm	Lateral and (slightly) opposed thumb configurations	Multigrasp → Requiring sound hand	1844	28	[46]
Blatchford and Blatchford (GB 345,340)	Lateral and opposed thumb configurations	Multigrasp → Requiring sound hand	1931	28	[62]
Northtrop Hand Model No. 2 (US 2,553,827)	Lateral and opposed thumb configurations	Multigrasp → Requiring sound hand	1951	28	[63]
Northtrop Hand Model No. 3 (US 2,549,074)	Lateral and opposed thumb configurations	Multigrasp → Requiring sound hand	1951	29	[64]
Northtrop Hand Model No. 5 (US 2,553,827))	Lateral and opposed thumb configurations	Multigrasp → Requiring sound hand	1951	30	[63]
Arm of Klingert	Blocking movement of particular fingers	Multigrasp → Requiring sound hand	18th	30	[51]
Pfister's second arm	Blocking movement of particular fingers	Multigrasp → Requiring sound hand	19th	30	[46]
Kuhn (GB 862,437)	Able to conduct pinch and power grasp	Multigrasp → Defined closing trajectory	1961	31	[66]
Troendle Hand	Thumb alignment of 120° → able to conduct pinch and power grasp	Multigrasp → Distinct thumb alignment	1917	31-32	[51]
Hand of Bethe	Able to conduct pinch and power grasp	Multigrasp → Default and secondary hand grasps	1917	32-33	[51]
Robinson (GB 116, 968)	Lateral and opposed thumb configurations	Multigrasp → Default and secondary hand grasps	1918	33-34	[67]
Winfrey (US 7,361,197)	Lateral and opposed thumb configurations; adaptive grips	Multigrasp → Default and secondary hand grasps; underactuated → floating pulleys	2008	34-36 37	[68]

Continuation Table 1

Device	Features	Category	Year	Pages	
Gosselin	Adaptive grips	Multigrasp → Underactuated Hand	2008	37	[73]
Laliberté	Adaptive grips	Multigrasp → Underactuated Hand	2010	37-39	[74]
Baril (WO 2013/185231 A1)	Adaptive grips	Multigrasp → Underactuated Hand	2013	37	[70]
McNaught and Bacon (WO 2013/076683)	Adaptive grips	Multigrasp → Underactuated Hand	2013	37	[75]
De Visser and Herder	Adaptive grips	Multigrasp → Underactuated Hand	2000	38	[76]
Belter and Dollar	Adaptive grips	Multigrasp → Underactuated Hand	2013	39-40	[55]
Dollar and Howe	Adaptive grips	Multigrasp → Underactuated Hand	2007	40	[77]
Zawodnik Hand	Toggle to switch stump rotation coupling between prehension and wrist rotation	Partially active wrists → Stump-controlled active wrist alignment	n/a	57	
Arm of Erlacher	Toggle to switch stump rotation coupling between prehension and wrist rotation	Partially active wrists → Stump-controlled active wrist alignment	n/a	57	[46, 51]
Carnes Hand for below-elbow amputees (US 1,046,966)	Partially active wrist flexion thru overloading of prehension cable when wrist flexion lock is released; having an additional control to operating wrist rotation lock; when wrist rotation freed coupled to elbow motion	Partially active wrists → Active wrist alignment based on overloading principle; Fully active wrists → Additional control cable	1912	57-58; 60	[46, 51, 82, 83]
Hosmer's 4-Functional Wrist	Control cable to operate wrist rotation lock; passive operation of wrist flexion lock; passive wrist alignment	Partially active wrists → Active lock operation via additional control cable	2002	58	[115]
Texas Assistive Devices' N-abler (US 7,048,768)	Control cable to operate wrist locks; passive wrist alignment (flexion and rotation) N-abler Version A); passive wrist flexion and active wrist rotation (N-abler Version B)	Partially active wrists → Active lock operation via additional control cable	2006	58-60	[100]

Continuation Table 1

Device	Features	Category	Year	Pages	
Arm of Béchard	Individual control cable and body movement for wrist rotation, but no detailed information	Fully active wrists → Additional control cable	1861	60	[51]
First arm of Mathieu	Individual control cable and body movement for wrist rotation, but no detailed information	Fully active wrists → Additional control cable	1860	60	[51]
Troendle Arm	Individual control cable and body movement for wrist rotation, but no detailed information	Fully active wrists → Additional control cable	1917	60	[51]
Motis (US 3,466,937)	Individual control cable and body movement for wrist rotation	Fully active wrists → Additional control cable	1969	60	[103]
Gear Drive of Norhrop Aircraft, Inc.	Using axillary control to alternate the responsibility of the control cable between prehension and wrist rotation	Fully active wrists → Axillary Control	1951	61-63	[65]
Northrop Aircraft's Gear Drive With Roller Lock (US 2,457,316)	Stump controlled wrist rotation with automatic lock	Fully active wrists → Stump controlled	1948	63-64	[104]
Northrop Aircraft's Reaction lock, Cable Drive-Wrist (US 2,638,604)	Stump controlled wrist rotation with automatic lock when prehension control cable is tensioned	Fully active wrists → Stump controlled	1953	64-65	[105]

The research aim of this literature review comprises two parts: first of all, it is investigated, if attempts have been made either in the past or more recently to equip body-powered prosthesis with additional DoF. Secondly, it is considered, why potential attempts are not realized nowadays. These two research aspects are both shortly addressed in Table 1. Furthermore, they will be separately, further elaborated in this discussion starting with the chronology of the design of body-powered prosthesis with multiple DoF's.

As Table 1 shows equipping body-powered prostheses with multiple DoFs in the form of different grasp patterns or wrist movements has a long history in scientific research on body-powered prosthesis. New literature has been repeatedly published in the course of time and so have devices appeared on the market. However, some distinct time periods can be identified, when no new body-powered developments with respect to multiple DoFs were introduced. These developments will be presented and analyzed in detail in the following. However, due to the lack of available literature critically investigating on the reasons of those waves of publications as well as market absences, the author is limited here to assumptions derived from historical events.

A large part of the multigrasp prostheses or wrist components, presented in this literature review, have been introduced before 1918. In the early multigrasp prostheses different grasp types were either achieved by means of multiple control cables, the sound hand or switching between default and secondary grasp type. Additional cables were also implemented to operate wrist movements. Alternatively, wrist flexion was realized by overloading the common control cable for prehension.
After the year 1918 a big gap can be noticed until 1931, when the patent *GB 345,340* was filed by Blatchford and Blatchford. The lack of new developments after 1918 is at first sight surprising since the year corresponds to the end of World War I, in which many war victims were left with the loss of upper or lower extremities. Consequently, the demand for prosthetic replacements was very high, which generally fostered the advancement of prostheses [116]. However, in this time period the design priorities had shifted. Post WWI it was important to restore the basic body functionality of as many amputees as possible to enable them to participate independently in everyday life rather than concentrate on appearance. Therefore, the desire of additional DoF existing in the form of complex multigrasp prostheses tailored to the need of its user had been pushed to the background. One concrete simple solution of that time was instead of equipping the war victims with a prosthesis to apply Krukenberg's surgical technique, by which the ulnar and the radius were split and covered with skin in order to create a pincer out of the amputee's stump [14, 46]. Thus, the amputee could use his/her own remaining muscles to operate the pincer. In addition to the proprioceptive feedback, common body-powered prostheses already facilitated, the amputee could receive the sense of touch with the Krukenberg pincer. However, the Krukenberg pincer was aesthetically very unpleasant. A second approach of that time period, which in turn involved a prosthetic device, is the control method of cineplasty. Cineplasty describes the surgical technique of creating a muscle channel by incising the upper arm muscle and covering it with skin. An ivory pin is positioned within this muscle channel and connected via cables to the hand prosthesis. Consequently, the movement and force of the muscle is directly transmitted to the prosthesis, which also improves the sensory feedback. However, both rising patient care techniques were aesthetically very unpleasant and required intensive hygienic care [12, 14, 46, 116, 117], which is why their importance diminished over the years. Since the Krukenberg pincer and cineplasty as direct muscle attachments are two totally different control techniques of prostheses compared to the body-powered or the myoelectric ones, they have not been considered before in the main part of this review.

A new wave of body-powered prostheses with multiple DoFs were introduced between WWII and the 1960's. In these new developments the implementation of multiple DoF via additional control cables or by requiring the sound were reconsidered. Furthermore, a multigrasp hand prosthesis was presented, which comprised a new functional principle of having a distinct closing trajectory. The approach of prosthetic wrist rotation was also refined at this point in time. Newly, prosthetic pronation and supination were operated by remaining rotation in the amputee's stump or by axillary control.
In the 1960's the end of body-powered prostheses up to recently marked the commercial introduction of myoelectric prostheses. The myoelectric prostheses possibly dispelled further research on body-powered prostheses, because they were considered to be superior. The operation of myoelectric

prostheses does not require any physical effort due to the electrical powered motors. Furthermore, the amputee can control both prehension movements (opening and closing) actively in contrast to the common body-powered prostheses. Due to independently movable fingers a more stable grip can be achieved in myoelectric prostheses. Moreover, additional DoFs could be added to these prosthetic types easily: first of all a switch could be implemented, whose manipulation changes the DoF to be operated by the myoelectric signals. This switch could be replaced by the idea of "*Four Channel*"-control, by which the currently controllable DoF is selected depending on the speed and intensity the muscle gets tensioned. Nowadays, the patient can also use co-contraction of his stump muscles to change the operation mode. Consequently, in myoelectric devices solely the side of amputation is used for prosthesis control, which is more natural and intuitive for the user. Moreover, the operation of multiple DoFs can be conducted very inconspicuous and does not pose any mental challenge, once the amputee has learned how to generally control a myoelectric prosthesis. This is in contrast to the implementations of multiple DoFs in body-powered prostheses and illustrates that this idea had been approached in an inadequate way.

In the last ten years research on body-powered prostheses with multiple DoFs has regained attention. A significant number of papers deals with so called "*underactuated hands*" [18], which appear to be successful examples of multigrasp prostheses. As outlined in chapter 4.2.1 the prosthetic fingers can adapted to irregular shaped objects by means of differential coupling. As soon as a finger experiences a predefined amount of resistant force, further applied input force is redirected to the adjacent finger/s. However, the amputee cannot choose intentionally a particular grip pattern at each time. Instead the hand solely adapts to the shape of the object and this might induce a change in gasp type. Consequently, underacutated hands support multiple grasp types, but not in an active manner. Hence, the underactuated hands do not present concrete solutions to the research questions.

Today, apart from two wrist devices (Hosmer's *4-Funcitonal Wrist* and Texas Assistive Devices' *N-Abler*) none of the multigrasp hands or the wrist components found in literature is currently commercially available. The two available ones do not record high sale figures despite apparent demand as emerged from a conversation with a representation of the medical store Horst Rattenhuber GmbH at the OT-World, the international trade fair of orthopedic and rehabilitation technology, in Leipzig May 3rd-6th 2016. Whereas the market absence of the body-powered prostheses with multiple DoFs, described in the more recent literature, can partially be explained by current publications being limited to describing prototypes, which still have to undergo a prolonged process until gaining market approval, the low demand in the two commercially available wrist devices results from an inadequate approach to the problem. In these devices the amputee can release the wrist locks by operating the corresponding control cable. Following this they require the sound hand two change the wrist alignment. These ways of realizing additional DoF are inadequate as will be illustrated in more detail in the second part of this discussion.

So far, the chronology of the development of body-powered prostheses with multiple DoF has been considered. It could be revealed, that the research of body-powered prosthesis with multiple DoF have been revived intermittently over time. Reasons for the intermissions were suggested. However, solely two slow-selling wrist devices are currently commercially available. Explanations why the body-powered attempts did not and do not prevail despite apparent demands will be approached in the following second part of this discussion. For this, each way of implementing additional DoFs as illustrated in Chapter 4.2 and Chapter 5.2 will be critically discussed.

The majority of the found body-powered devices with multiple DoFs require the sound hand either to change the thumb position and hereby the grasp type, to block the movement of particular fingers, to operate the wrist lock or to actually align the wrist position. Requiring the sound hand to manipulate a DoF of the contralateral prosthesis is counterintuitive and does not convey a natural feeling to the amputee. Moreover, it prevents bilateral amputees from operating all features of the device. Hence, manual operation of additional DoFs is not an acceptable solution.
Another common method to realize different grasp types or wrist movement is the usage of multiple

[18] The principle of underactuation is also applied to myoelectric prostheses. However, these will be disregarded in this review.

control cables. For example, the prosthetic hand designed by G.R. Tureman, Jr. (see Subsection 4.2.1) comprises four different cables: one cable solely for thumb movement, one cable to control only the index finger, one cable for index and middle finger and one cable to operate all fingers simultaneously. To each control cable a distinct body motion is allocated. Ensuring that only the desired control cable is operated at a time bears a big mental challenge for the user. Amputees probably perceive the variety of control cables as cumbersome as well as tiring and hence, abolish their usage. Therefore, the implementation of additional control cables is also not the right approach to equip body-powered prosthesis with additional DoFs.
The design patented by Kuhn enables pinch as well as power grasp by having a specific closing trajectory of the two movable fingers approaching each other and the opposing stationary one (see Subsection 4.2.1). Consequently, an object can either be pinched between the space of the movable fingers or positioned between all three fingers simulating a power grasp. However, the appearance and closing motion of this device resemble animal claws rather than a human hand. Due to its unnatural cosmesis this device probably could not gain acceptance.
Besides other devices like the *Troendle Hand* (Figure 28), *Hand of Bethe* (Figure 29) or the hand designed by R. Winfrey (Figure 31) could be found, which introduce very interesting ways of facilitating multiple grip patterns. As explained in Subsection 4.2.1 the *Troendle Hand* had a characteristic thumb alignment of 120° to the middle finger axis. In this way, the grasp type was changed based on the hand opening width.
The *Hand of Bethe* and the hand designed by R. Winfrey both have a default grasp type, but change to a secondary one depending on acting opposing forces. The applied mechanisms in these prostheses are generally very interesting solution approaches since the change of grasp pattern happens in a very inconspicuous manner appearing very natural. Despite these benefits, the prostheses bear the disadvantage that the amputee cannot actively select between pinch and power grasp. Instead, the grip pattern is changed in the course of the prehension movement due to the shape of the object. Consequently, the user is not truly able to control the DoFs of the prosthesis.
Northrop Aircraft Inc. has introduced another fascinating solution to operate prosthetic pronation and supination, namely by means of remaining natural stump rotation. The devices are equipped with a step-up system to increase the ratio between terminal device and stump rotation. Furthermore, the designs comprise an automatic lock to secure the selected wrist alignment in place. This principle is a successful, very natural and intuitive approach to restore wrist rotation. However, such a device can only be used by below-elbow amputees with a long stump since they solely have remaining stump rotation (see Figure 10). As this solution is limited to a specific target group and niether applicable for below-elbow patients with a short stump nor for patients with amputations above the elbow, this appraoch does not fulfill the idea of the author of universal usage.
The same company has also developed a device, in which axillary control (see Subsection 5.2.2.1) is used to alternate the responsibility of the control cable between prehension and wrist rotation. To exercise the axillary control a button is positioned in the arm pit, which the amputee can operate by adducting his/her upper arm. Since the button positioned in the arm pit can be perceived as very uncomfortable as well as the button operation might be very cumbersome, patients might avoid using such a device.
Two last approaches worthwhile mentioning from the literature review are the idea of coupling wrist rotation to the elbow flexion or wrist flexion based on an overload principle as implemented in the *Carnes Arms*. These approaches seem to have high potential. Nevertheless, the mechanics of the complete Carnes Arms tend to be very complex and fragile. It might have been the case that the manufacturing and maintenance of this prosthesis type were too expensive due to the high complexity or the knowledge of repairing, which is why this prosthesis type is not available anymore.

To sum up, this literature review has presented different approaches to implement multiple grasp types or wrist motion into body-powered prosthesis. Yet, none of the body-powered attempts either currently commercially available, currently discussed in the scientific community or described in old literature present an optimal solution to the customers' needs since they are either mentally challenging, counterintuitive, aesthetically unpleasant or solely restricted to a small group of amputees.
The author still sees high potential in equipping body-powered prostheses with multiple DoFs, because it could lead to a cheaper, more robust and light-weight alternative of the myoelectric devices. Since a body-powered prosthesis with multiple DoFs does not include any electrical motors, it will be indepen-

dent from external batteries and thus less inconvenient as no regular charging is required. Furthermore, it bestows the user with proprioceptive feedback, which the myoelectric devices lack. Since the author believes that idea of a body-powered prosthesis with multiple DoFs has so far been approached in an inadequate way, she suggests to follow the example of the myoelectric control method. Compared to the body-powered prosthesis the way multiple DoFs are implemented in myoelectric ones appears very easy and intuitive.
In order to expand the advantages of body-powered prosthesis, it is desirable to have a similar simple and little mentally challenging solution to control and alternate multiple DoFs with body-powered prostheses: **a body-powered co-contraction equivalent**.
In this direction attempts were made in the form of simply adding a myoelectric controlled switch to a body-powered prosthesis as described in Chapter 4.3 and Chapter 5.3. However, in the opinion of the author a hybrid control cannot be the solution since combining both methods does not really improve the prosthesis significantly. When adding the myoelectric control to a body-powered prosthesis, a couple of advantages of body-powered prosthesis will cease to exist: for example the price of the device will raise tremendously, the weight of the device will increase and the amputee needs to remember to recharge the external power source of his/her device. Hence, the author rather suggests to search for a **mechanical switching mechanism comparable to the myoelectric signals to control multiple DoFs**.

To conclude, in the absence of any prosthesis combining the advantages of body-powered prostheses with the myoelectric one of multiple DoFs, the author suggests to design a mechanical hand mechanism, which can be used to select different grasp patterns or to switch the control mode of the prostheses between prehension and wrist operation.
This body-powered co-contraction equivalent requires two characteristics: a secure selection of a mode and the control of the chosen mode in an active manner. A switching device fulfilling these requirements will be elaborated in the scope of the final project of the author to obtain her Master degree.
The designs depicted in this literature shall hereby serve as sources of inspiration for a potential body-powered co-contraction equivalent. Especially, a couple of VO/VC devices like e.g. the *Carnes Hand for above-elbow amputees* (Figure 38) or the prototype designed by Motis (Figure 55) can reveal some possible solutions how to implement an active switching mechanism. Furthermore, body-powered devices, which already comprise a switching or locking mechanism such as VC-locks, hooks with altering maximal grip strengths or prosthetic elbows, might be worthwhile re-examining. Apart from devices from the field of prosthetics an old light pull switch or a ballpoint pen might provide suitable solutions. Consequently, the author plans to consider switches in the field of prosthesis, but also to think outside the box to come up with possible solutions for a body-powered co-contraction equivalent.

Appendices

A. Paper selection process

Flow diagrams representing the paper selection processes of the three additional search rounds are presented.

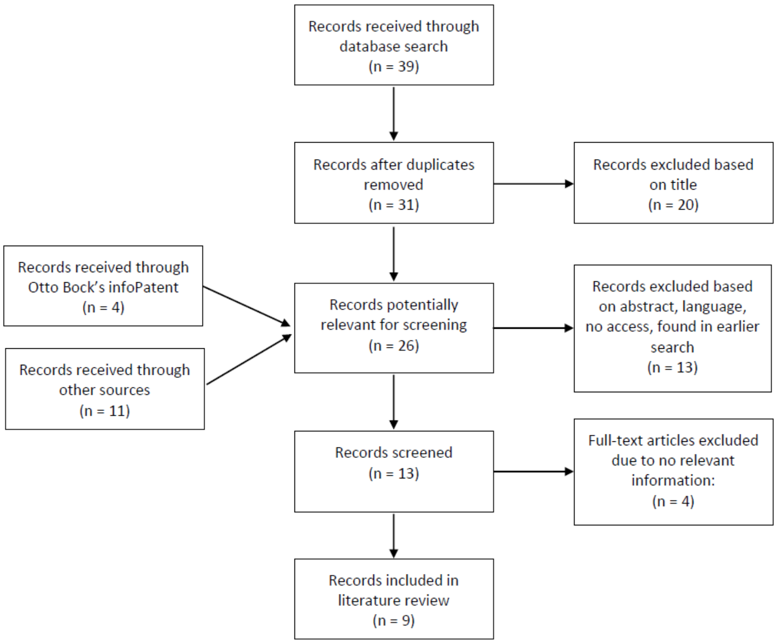

Figure 60: Flow diagram illustrating the results of the literature search regarding underactuated hands and the paper selection process

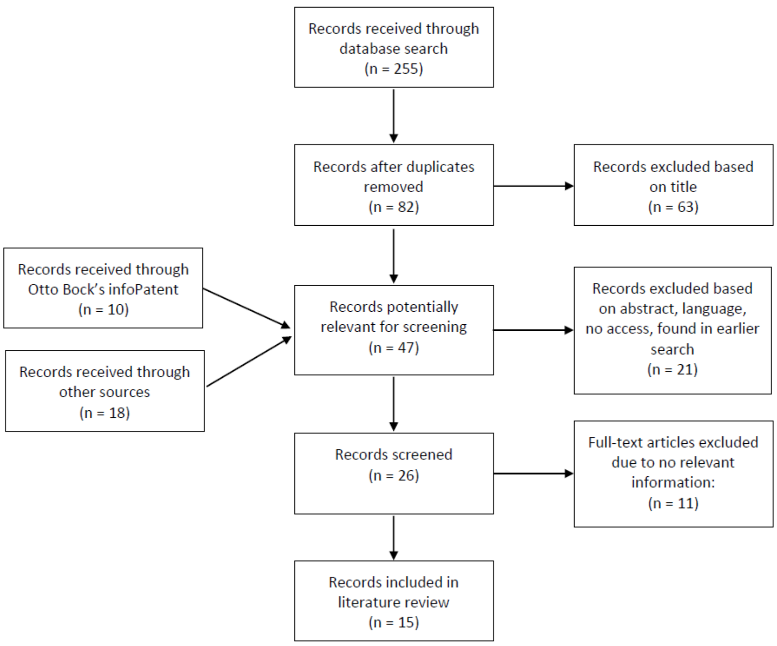

Figure 61: Flow diagram illustrating the results of the literature search regarding VO/VC-hands and the paper selection process

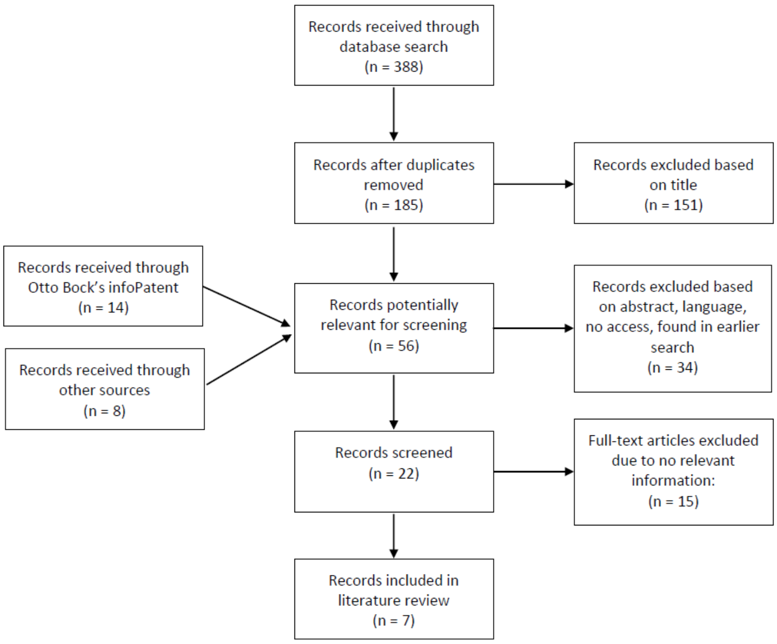

Figure 62: Flow diagram illustrating the results of the literature search regarding prosthetic wrists and the paper selection process

B. Overview VO/VC-devices

A table illustrating all VO/VC-devices depicted in this literature review is presented on the following pages.

Continuation Table 1

Device	Features	Category	Year	Pages	
LeBlanc	Two-way control; able to conduct pinch and power grasp	VO/VC → Simultaneous	1987	41	[80]
Arm of Dalisch	Two-way control by stump rotation	VO/VC → Reversed Body Movement	1857	42	[46]
Hand of Härtel	Two-way control by stump rotation	VO/VC → Reversed Body Movement	1917	42	[46]
Rotational controlled Hand of Leiter	Two-way control by stump rotation	VO/VC → Reversed Body Movement	n/a	42	[46]
Zawodnik Hand	Two-way control by stump rotation; toggle to switch stump rotation coupling between prehension and wrist rotation	VO/VC → Reversed Body Movement; Partially active wrists → Stump-controlled active wrist alignment	n/a	42; 57	
Arm of Erlacher	Two-way control by stump rotation; toggle to switch stump rotation coupling between prehension and wrist rotation	VO/VC → Reversed Body Movement; Partially active wrists → Stump-controlled active wrist alignment	n/a	42; 57	[46, 51]
Hand of Charriére	Two-way control due to rigid connections	VO/VC → Reversed Body Movements	1860	42	[46]
Hand of Troschinski	Two-way control due to rigid connections	VO/VC → Reversed Body Movements	n/a	42	[46]
Elbow controlled Hand of Leiter	Two-way control due to rigid connections	VO/VC → Reversed Body Movements	n/a	42	[46]
Arm of Mietens	Two-way control due to rigid connections	VO/VC → Reversed Body Movements	n/a	42	[46]
Arm of Jaks	Two-way control due to rigid connections	VO/VC → Reversed Body Movements	n/a	42	[46]
Carnes Hand for below-elbow amputees (US 1,046,966)	Two-way control by having to control cables; partially active wrist flexion thru overloading of prehension cable when wrist flexion lock is released; having an additional control to operating wrist rotation lock; when wrist rotation freed coupled to elbow motion	VO/VC → Reversed Body Movement; artially active wrists → Active wrist alignment based on overloading principle; Fully active wrists → Additional control cable	1912	42-43; 57-58; 60	[46, 51, 82, 83]
Carnes Hand for above-elbow amputees	Two-way control by having an altering mechanism changing the responsibility of the control cable	VO/VC → Sequential Switch	1913	43-45	[46, 51, 83]
Hand of Dalisch	Two-way control	VO/VC → Varying in the Range of the Control Motion	n/a	45	[46]

Continuation Table 1

Device	Features	Category	Year	Pages	
Nelson and LeBlanc (US 4,990,162)	Two-way control; able to conduct pinch and power grasp	VO/VC → Varying in the Range of the Control Motion	1991	45-46	[86]
Open Prosthetic Project concept 1	Two-way control (solely conceptual solution)	VO/VC → Varying in the Range of the Control Motion	2008	46-47	[87]
Open Prosthetic Project concept 2	Two-way control (solely conceptual solution)	VO/VC → Manual Switch	2008	47	[87]
Sullivan	Two-way control	VO/VC → Manual Switch	2011	47-48	[40]
Veatch (US2015/0021947)	Two-way control	VO/VC → Manual Switch	2015	48-49	[88]
Sensinger (US2014/0081425)	Two-way control	VO/VC → Manual Switch	2013	49-51	[38, 78, 79, 89]
Veatch and Scott (US 7,341,295)	Two-way control	VO/VC → Manual Switch	2008	51-53	[90]

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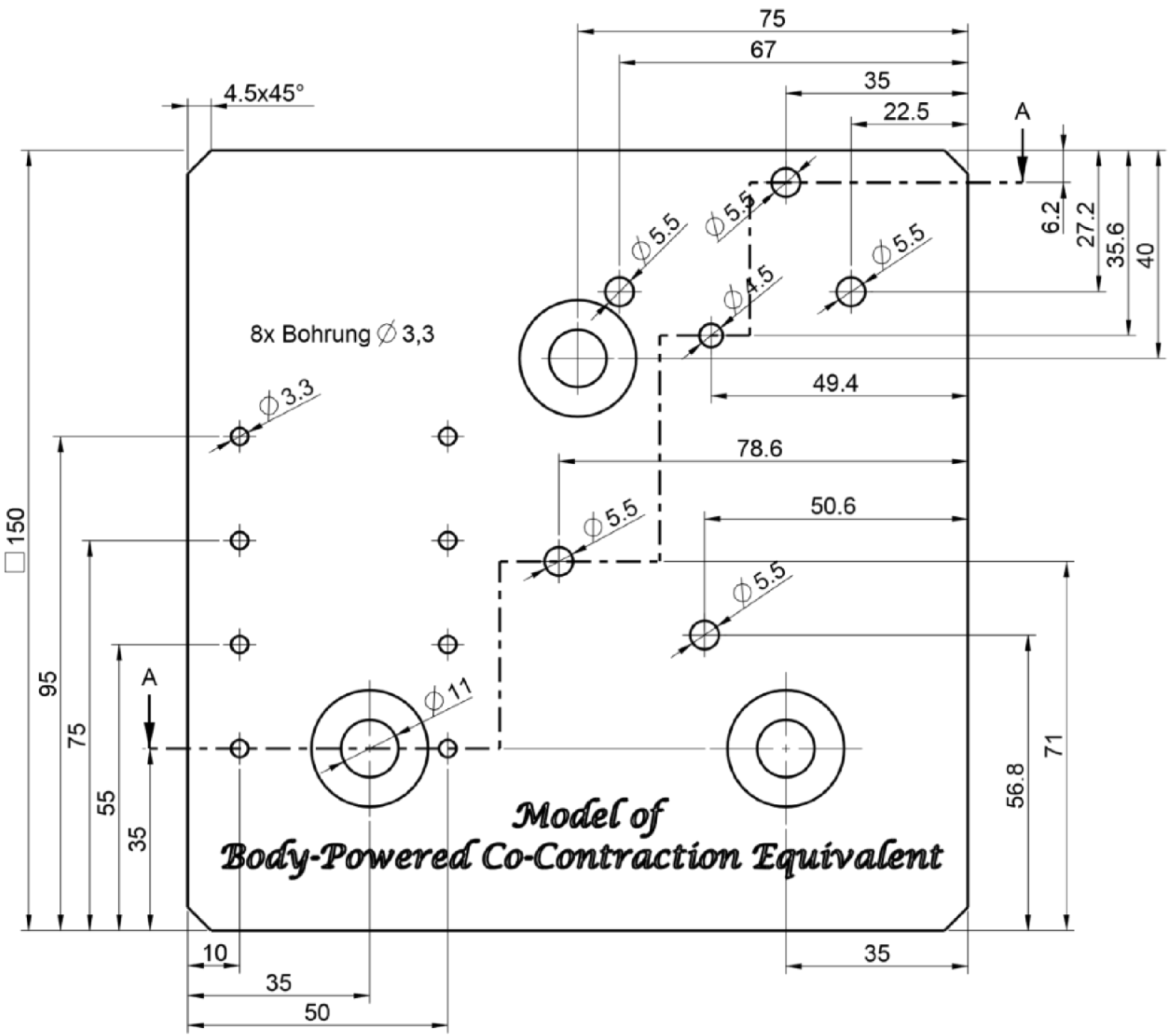
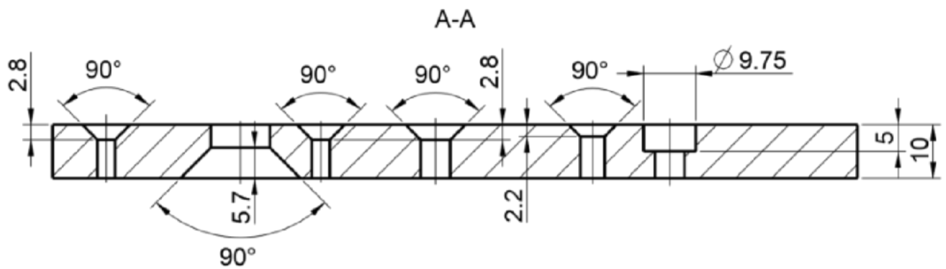
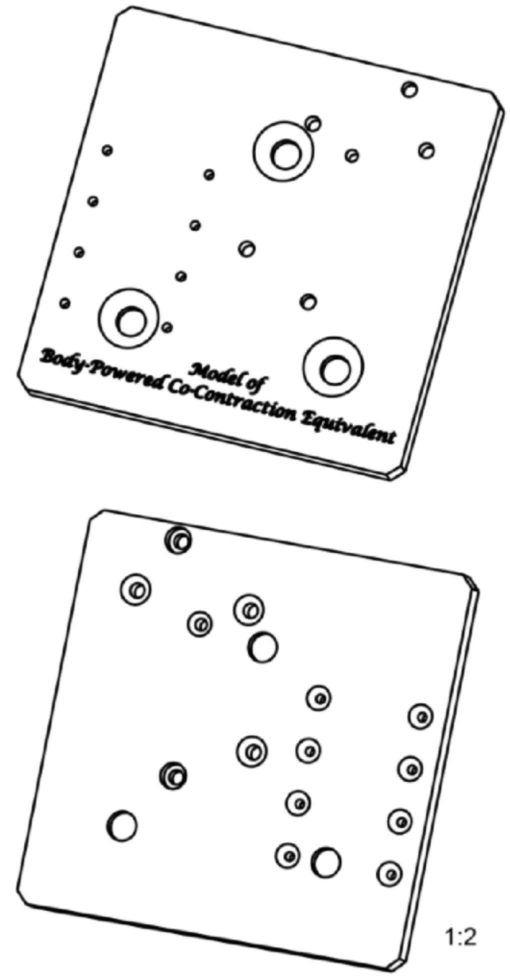
Technical Drawings







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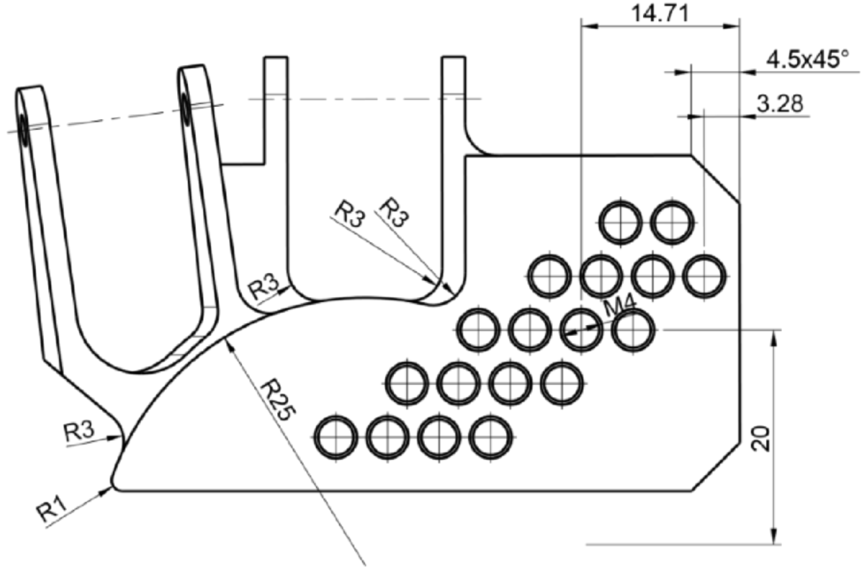

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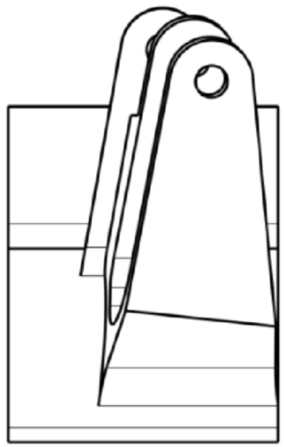

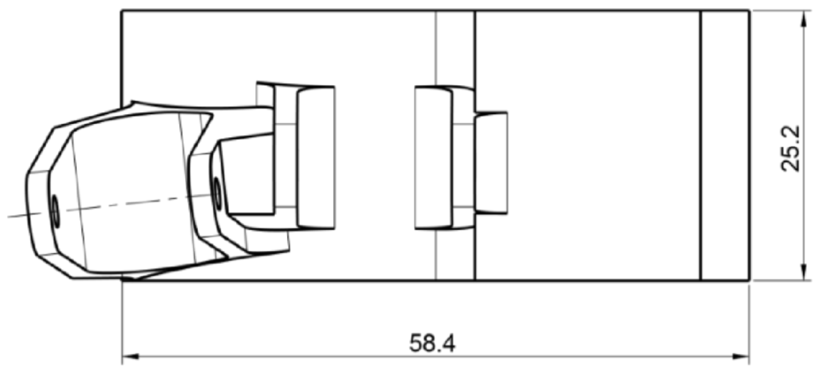

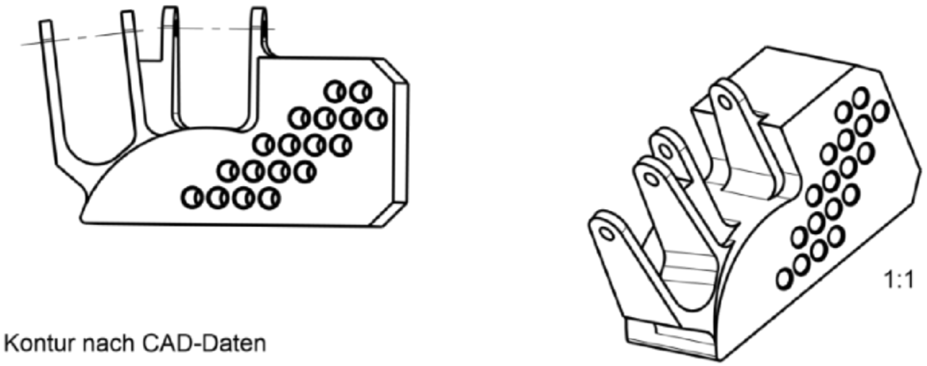

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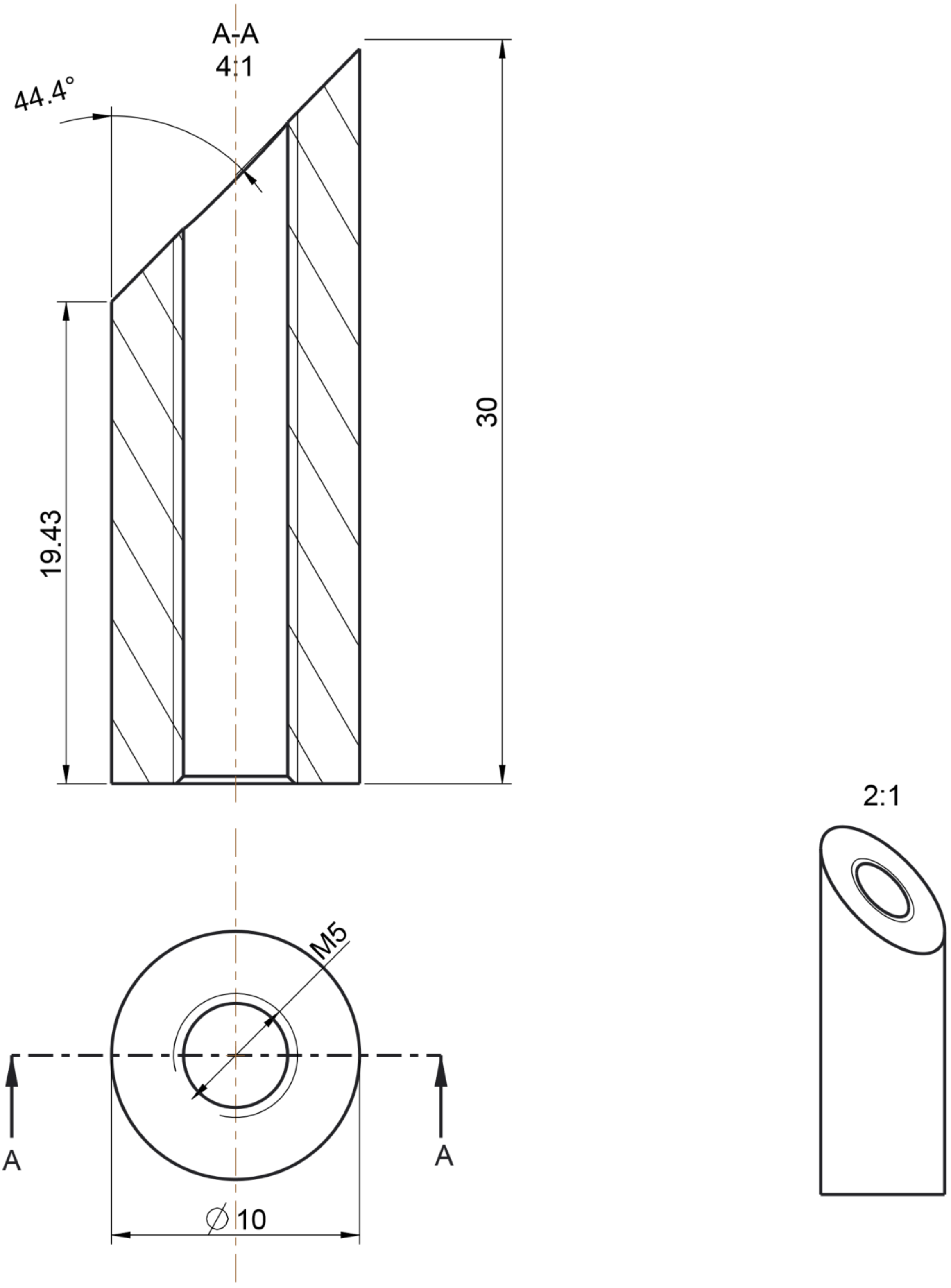


Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Bierbaum	Bierbaum		1:1	A4

ottobock.

Otto Bock HealthCare GmbH
Duderstadt

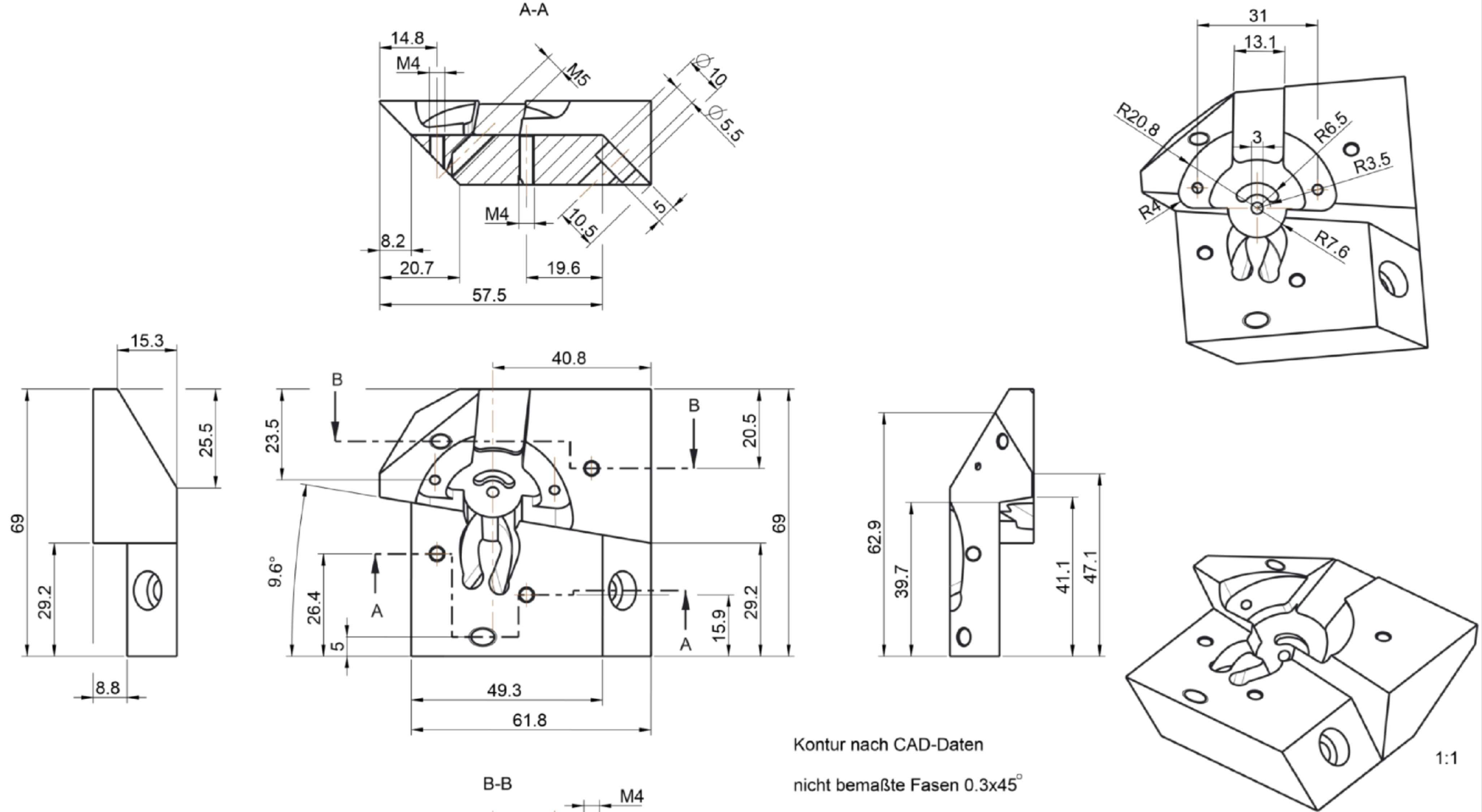
Materialnummer/Materialnumber

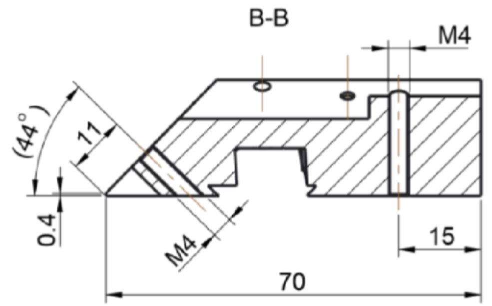
Materialbezeichnung/Materialdescription

Dokumentart/Document type: Einzelteilzeichnung/ detail drawing

Änd./Rev.	Datum/Date	Blatt/Sheet
	20170225	1/1

Filename: STUETZE_DAUMEN





Kontur nach CAD-Daten

nicht bemaßte Fasen 0.3x45°

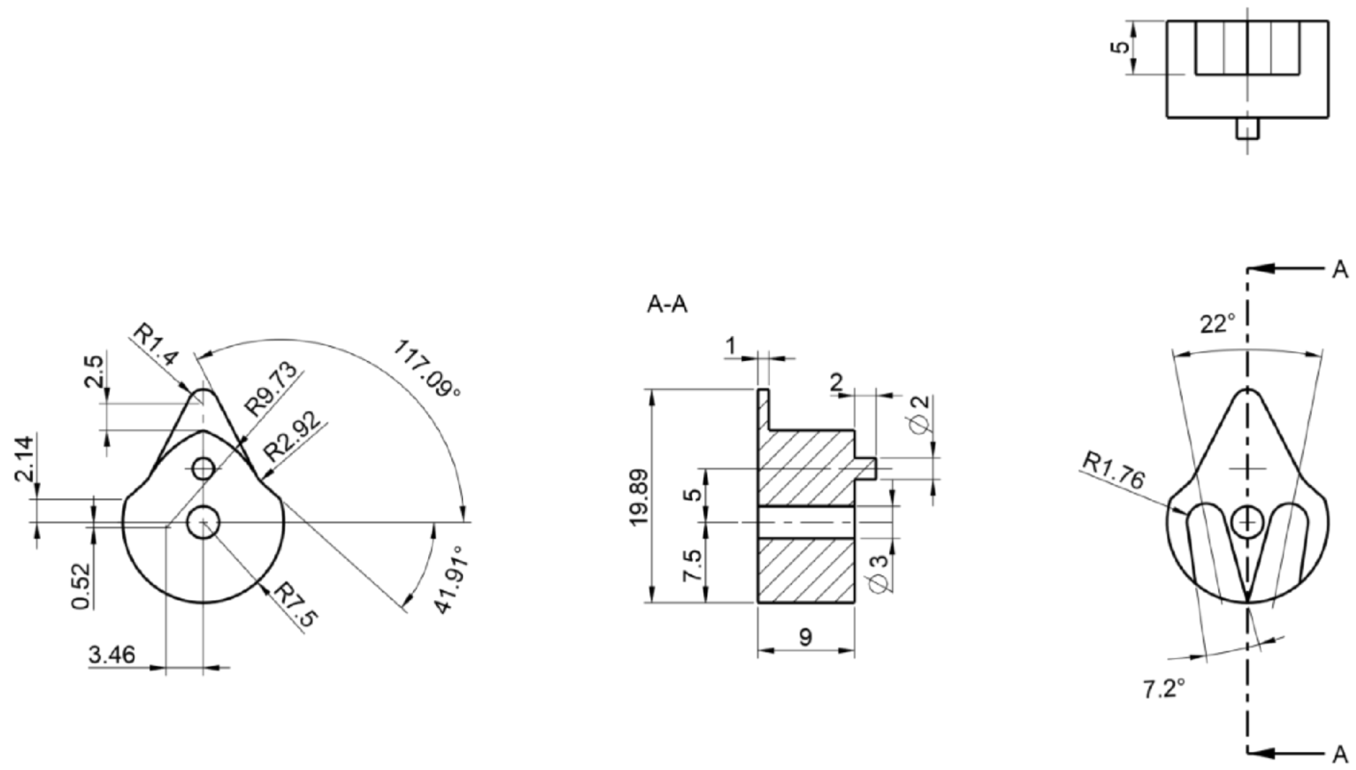
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		1:1	A3

	Materialnummer/Materialnumber	Dokumentart/Document type		
ottobock.		Einzelteilzeichnung/ detail drawing		
	Materialbezeichnung/Materialdescription	Änd./Rev.	Datum/Date	Blatt/Sheet
Otto Bock HealthCare GmbH Duderstadt		0	20160103	1/1

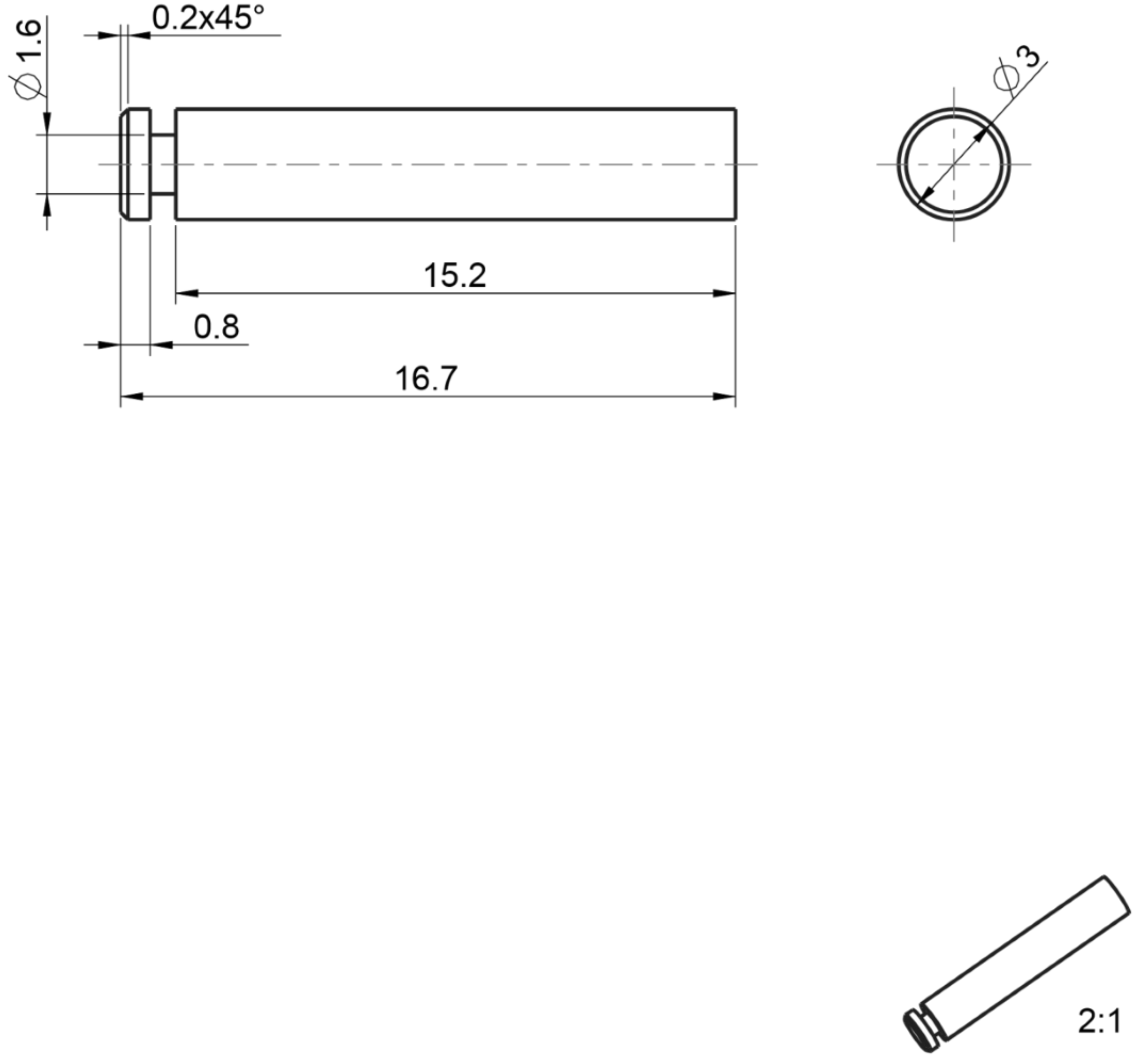
Filename: V4_DIRECTING_PLATE_ZUSAMMEN



Kontur nach CAD-Daten

Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Stahl Werkstoff/ Material spec.
Schutzvermerk/Copyright DIN ISO 16016	Allgemeintoleranz/General tolerance DIN ISO 2768-mK	Oberflächenbeschaffenheit/Surface texture DIN EN ISO 1302	Werkstückkanten/Edges DIN ISO 13715		
Gezeichnet/Drawn by Bause	Konstrukteur/Constr. eng. Bierbaum	PV/Product Resp.	Maßstab/Scale 2:1	Format/Format A3	
ottobock. Otto Bock HealthCare GmbH Duderstadt	Materialnummer/Materialnumber Materialbezeichnung/Materialdescription	Dokumentart/Document type Einzelteilzeichnung/ detail drawing	Änd./Rev. 0	Datum/Date 20170103	Blatt/Sheet 1/1

Filename: V4_DIRECTOR_PUSHED_RUND



Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		5:1	A4

ottobock.

Otto Bock HealthCare GmbH
Duderstadt

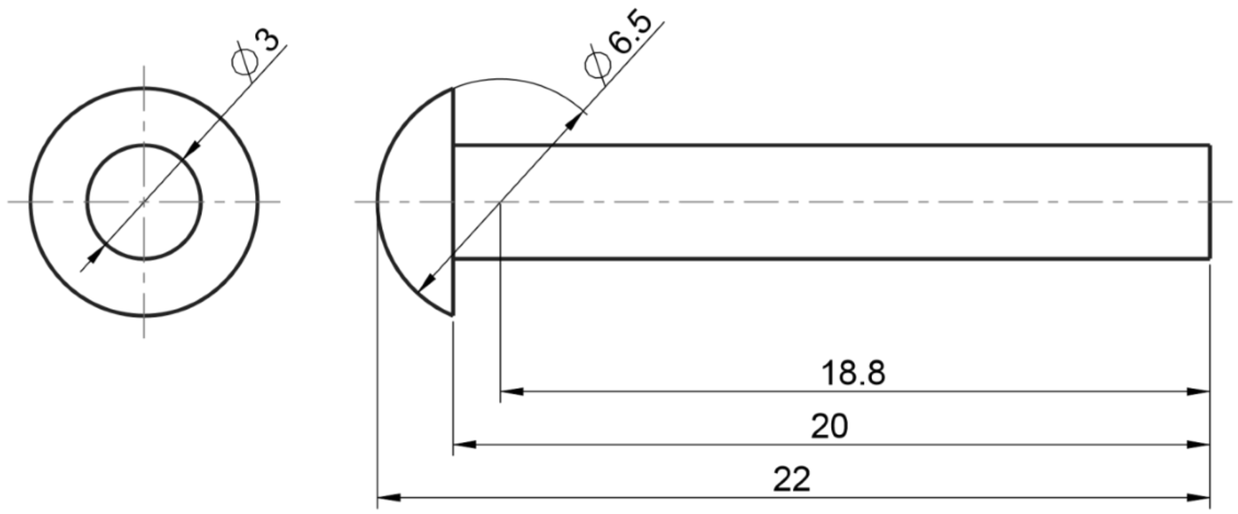
Materialnummer/Materialnumber

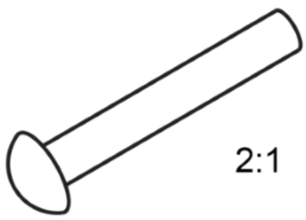
Dokumentart/Document type
Einzelteilzeichnung/ detail drawing

Materialbezeichnung/Materialdescription

Änd./Rev.	Datum/Date	Blatt/Sheet
0	20170106	1/1

Filename: V4_DREHACHSE





2:1

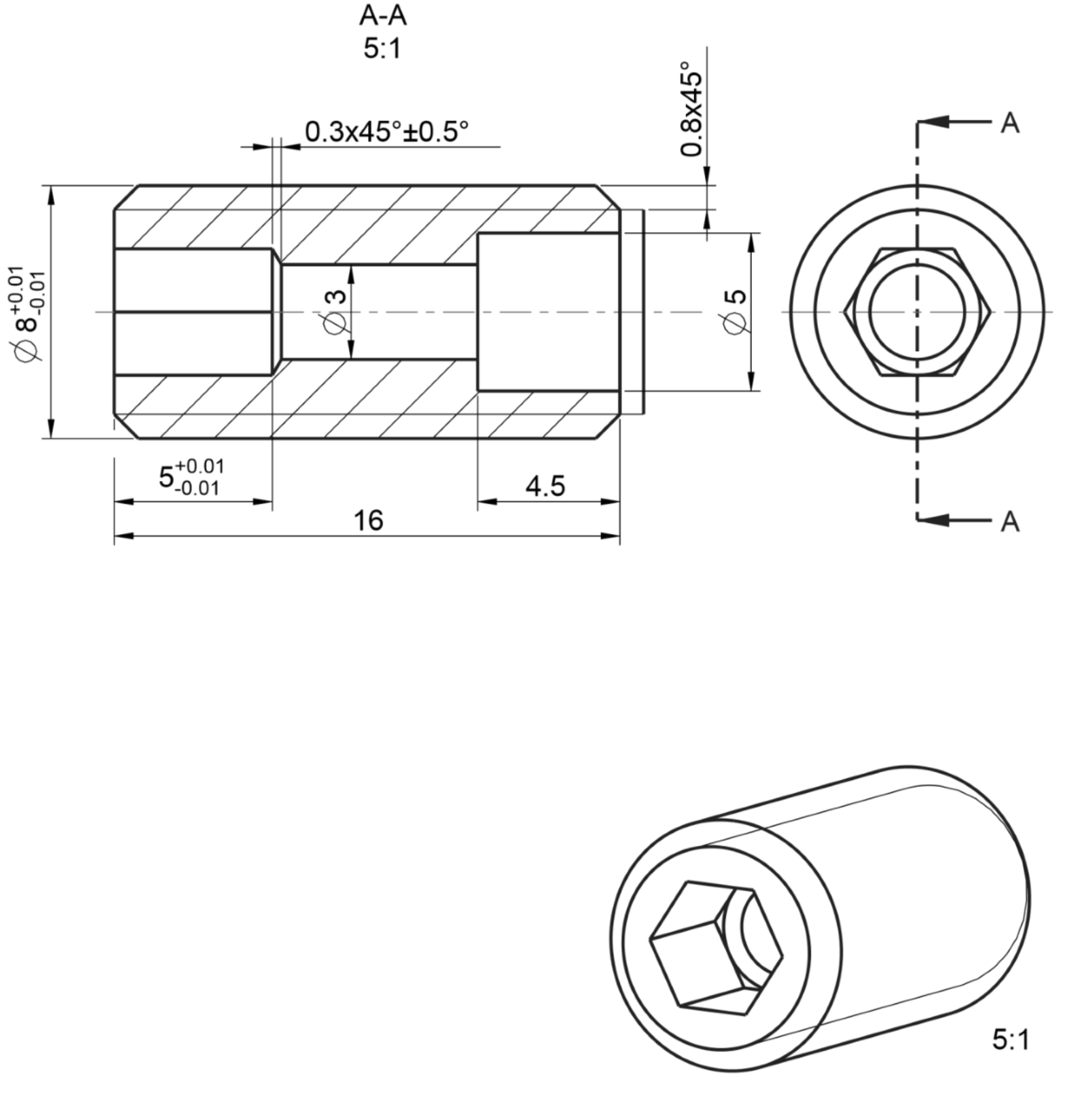
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		5:1	A4

ottobock.	Materialnummer/Materialnumber	Dokumentart/Document type Einzelteilzeichnung/ detail drawing		
Otto Bock HealthCare GmbH Duderstadt	Materialbezeichnung/Materialdescription	Änd./Rev. 0	Datum/Date 20170106	Blatt/Sheet 1/1

Filename: V4_PUSH_ELEMENT



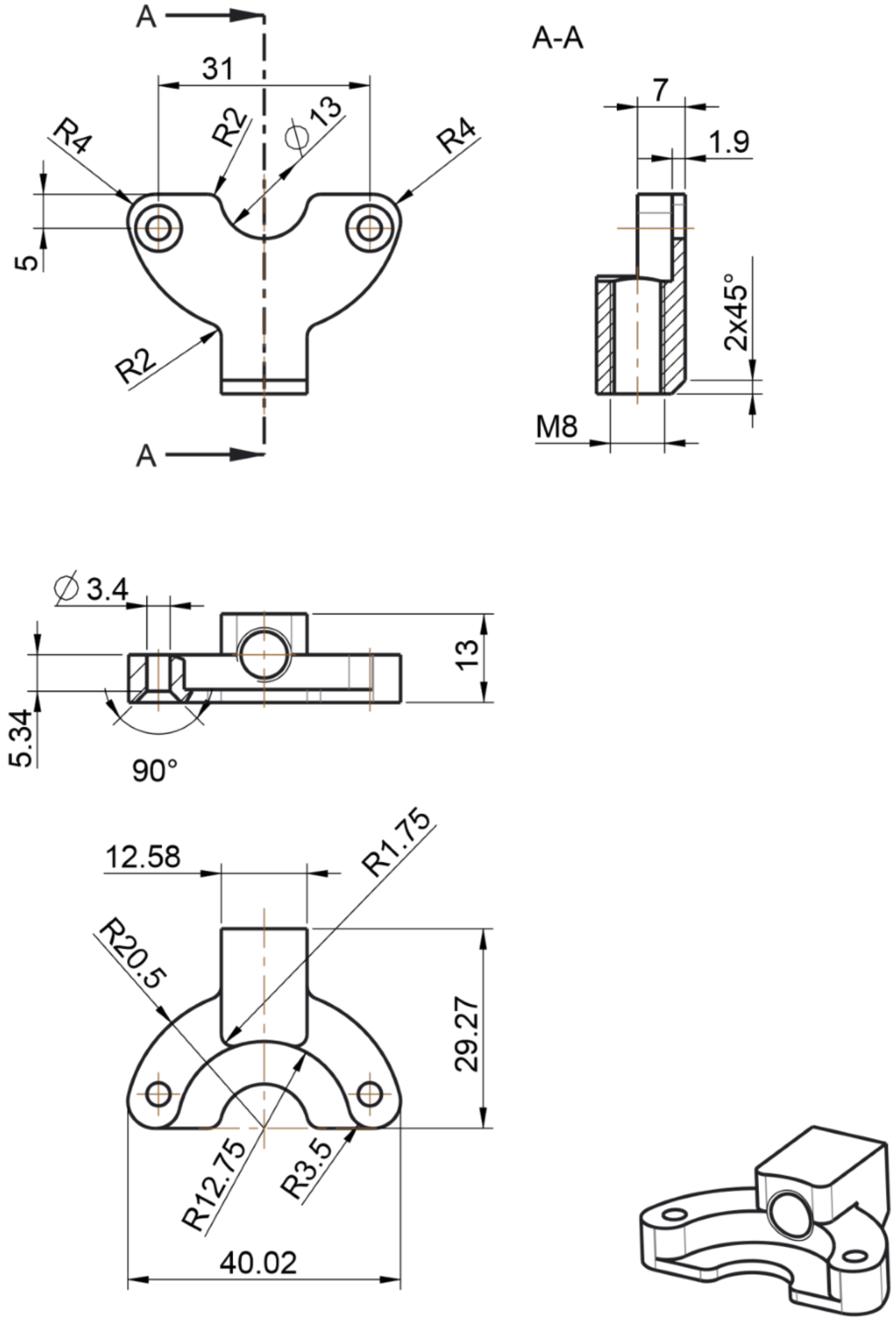
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		1:1	A4

ottobock.	Materialnummer/Materialnumber	Dokumentart/Document type: Einzelteilzeichnung/detail drawing		
Otto Bock HealthCare GmbH Duderstadt	Materialbezeichnung/Materialdescription	Änd./Rev.: 0	Datum/Date: 20170106	Blatt/Sheet: 1/1

Filename: V4_501G7-M8X18



Kontur nach CAD-Daten

Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.
					POM

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Bause	Bierbaum		1:1	A4

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Otto Bock HealthCare GmbH
Duderstadt

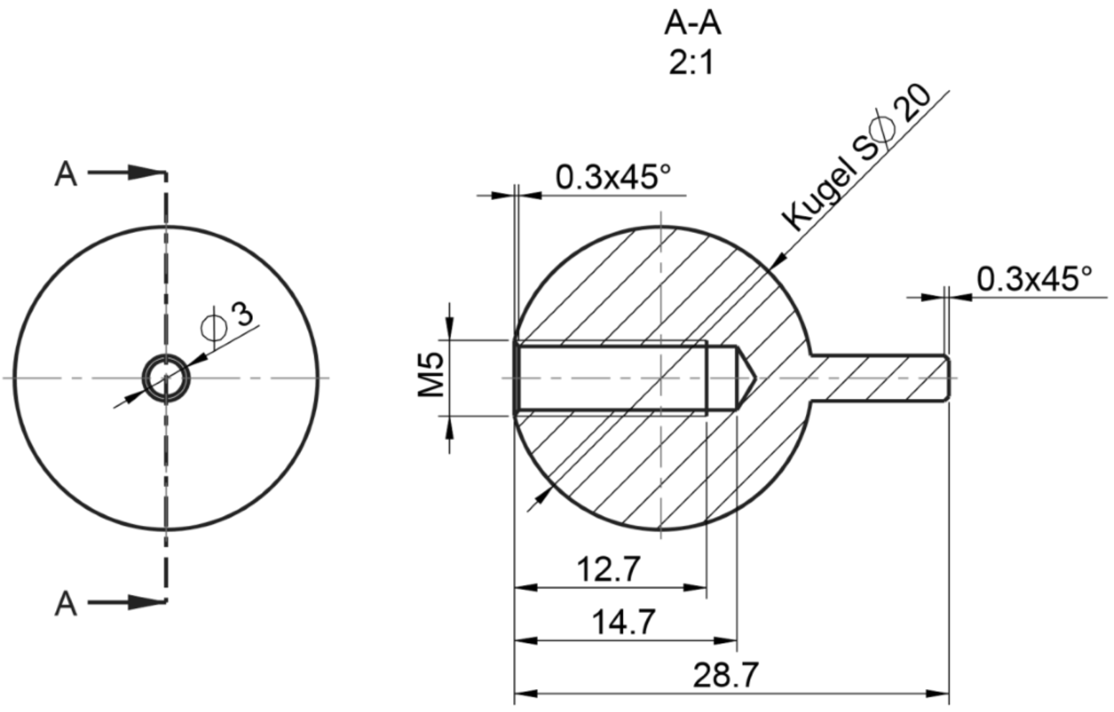
Materialnummer/Materialnumber

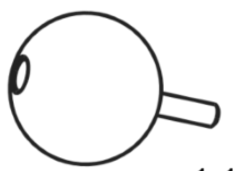
Dokumentart/Document type
Einzelteilzeichnung/ detail drawing

Materialbezeichnung/Materialdescription

Änd./Rev.	Datum/Date	Blatt/Sheet
0	20170104	1/1

Filename: V4_DIRECTOR_DECKEL





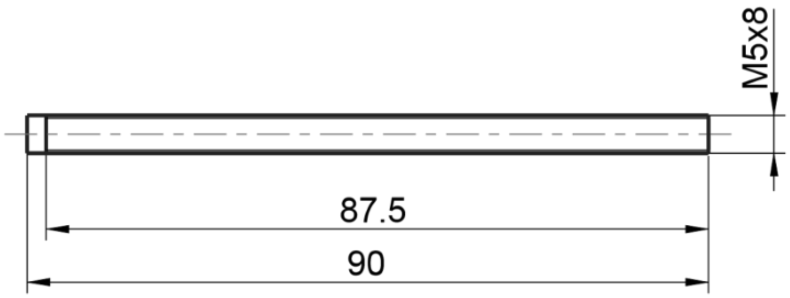
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

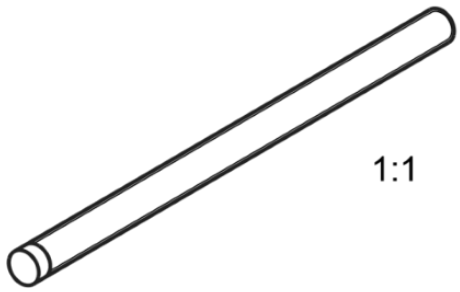
Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		2:1	A4

ottobock.	Materialnummer/Materialnumber	Dokumentart/Document type Einzelteilzeichnung/ detail drawing		
Otto Bock HealthCare GmbH Duderstadt	Materialbezeichnung/Materialdescription	Änd./Rev. 0	Datum/Date 20170112	Blatt/Sheet 1/1

Filename: CP_KUGEL_DAUMEN_





1:1

Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		1:1	A4

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Duderstadt

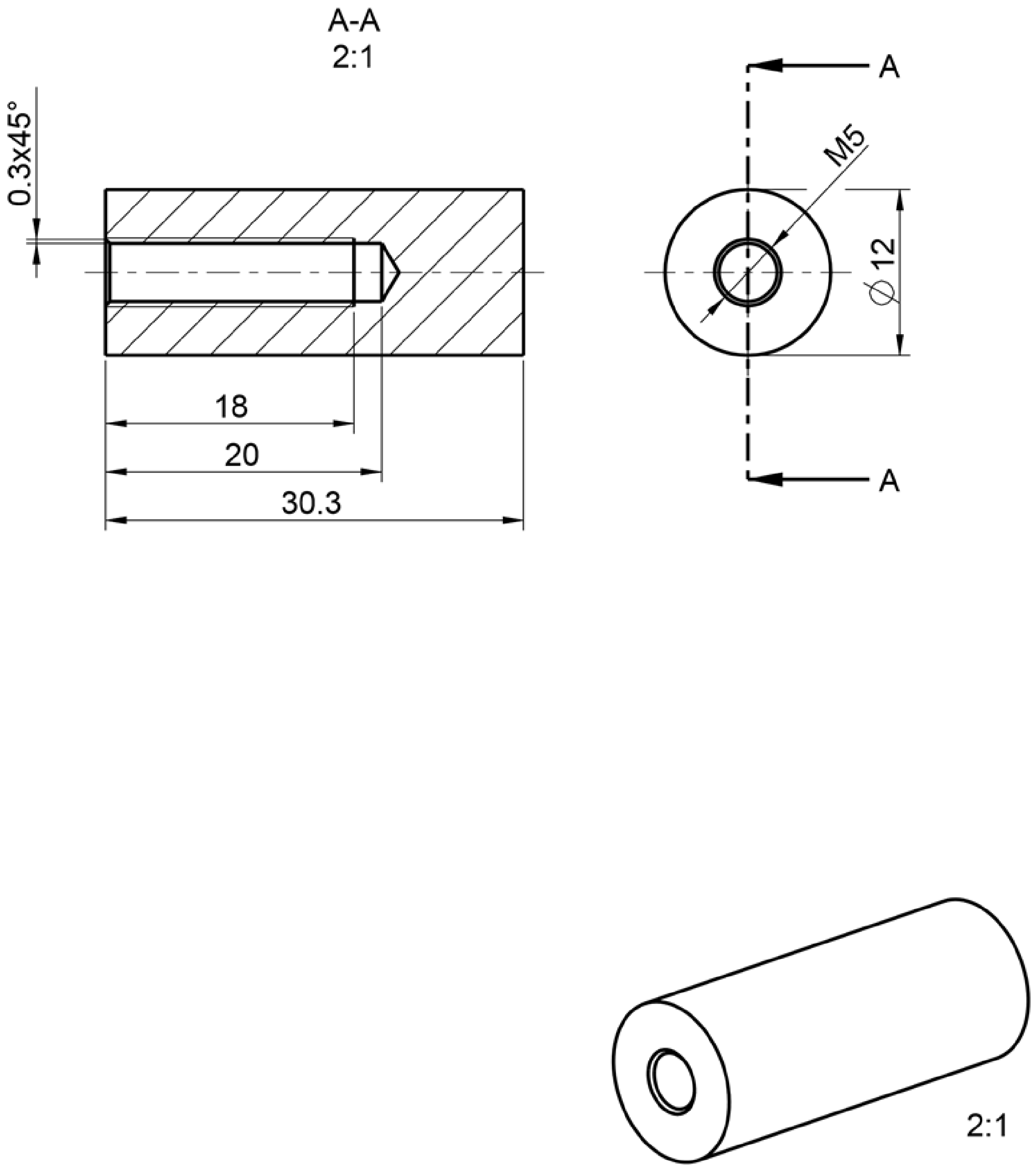
Materialnummer/Materialnumber

Materialbezeichnung/Materialdescription

Dokumentart/Document type
Einzelteilzeichnung/ detail drawing

Änd./Rev.	Datum/Date	Blatt/Sheet
0	20170106	1/1

Filename: CP_ORTSFESTER_DAUMEN_



Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		2:1	A4

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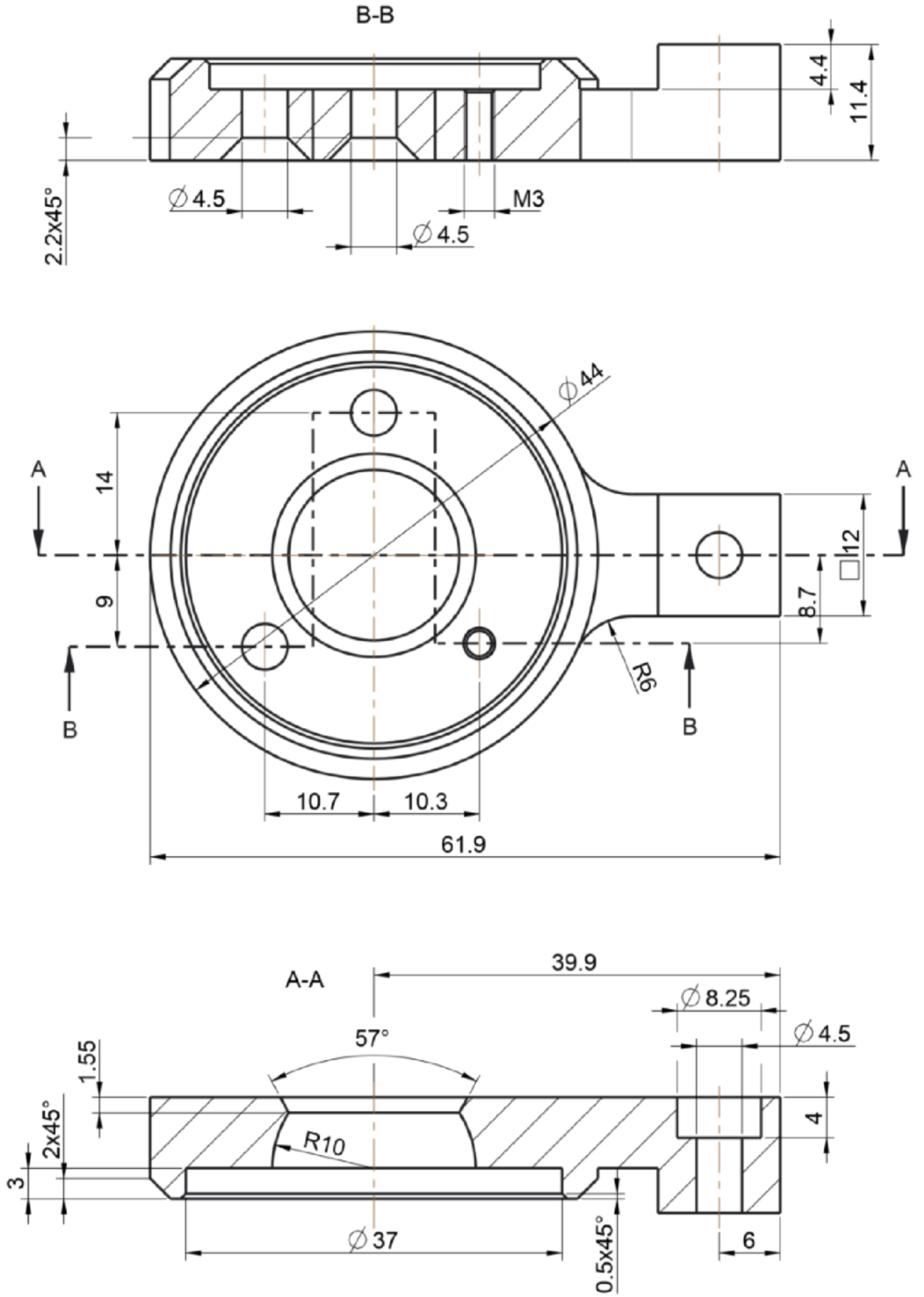
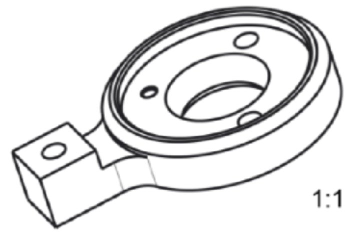
Materialnummer/Materialnumber	Dokumentart/Document type		
	Einzelteilzeichnung/ detail drawing		
Materialbezeichnung/Materialdescription	Änd./Rev.	Datum/Date	Blatt/Sheet
	0	20170106	1/1

Filename: CP_DAUMENSPITZE





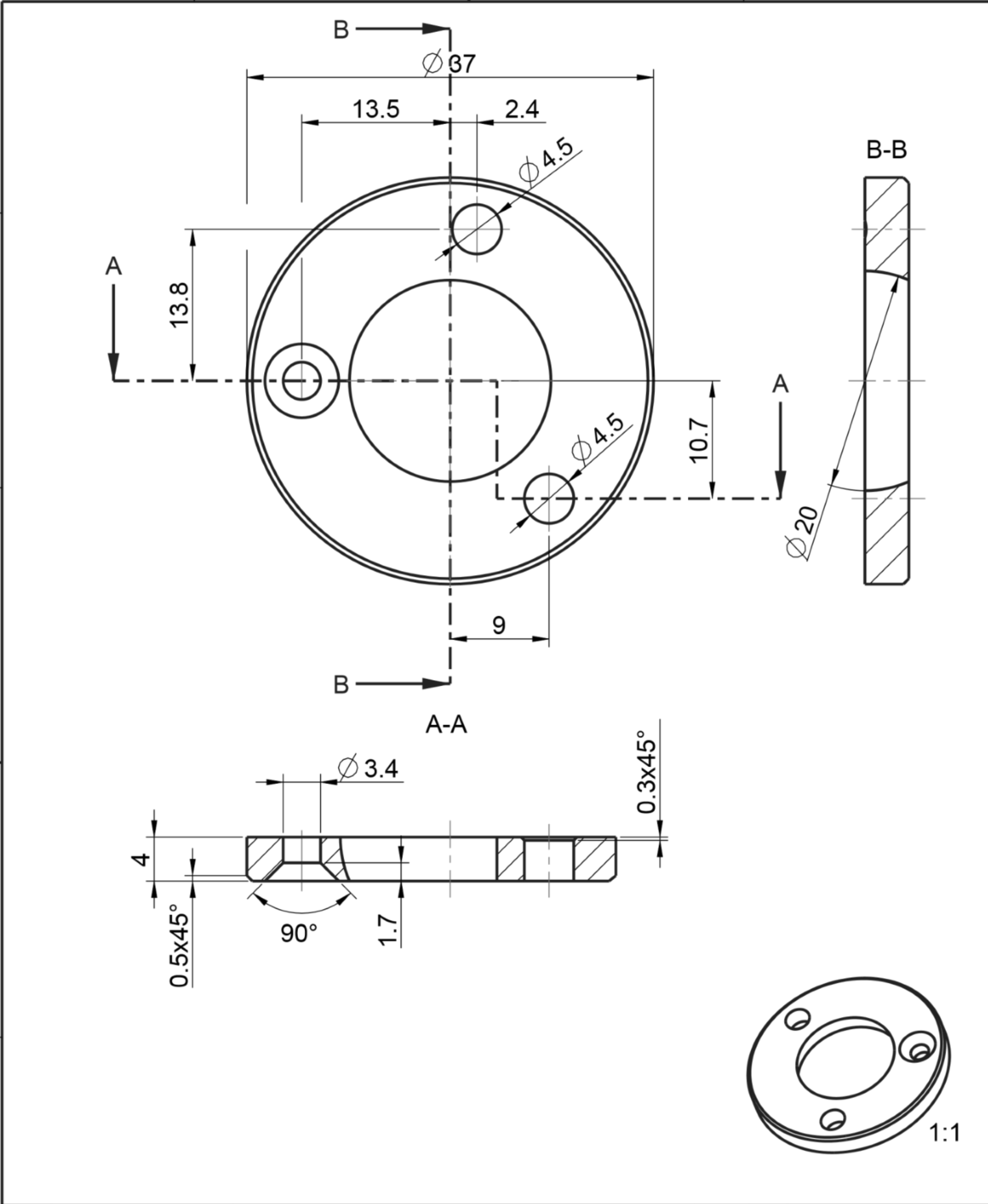
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		2:1	A3

ottobock.	Materialnummer/Materialnumber	Dokumentart/Document type: Einzelteilzeichnung/ detail drawing		
Otto Bock HealthCare GmbH Duderstadt	Materialbezeichnung/Materialdescription	Änd./Rev.: 0	Datum/Date: 20170104	Blatt/Sheet: 1/1

Filename: CP_KUGEL_LAGERUNG_DECKEL



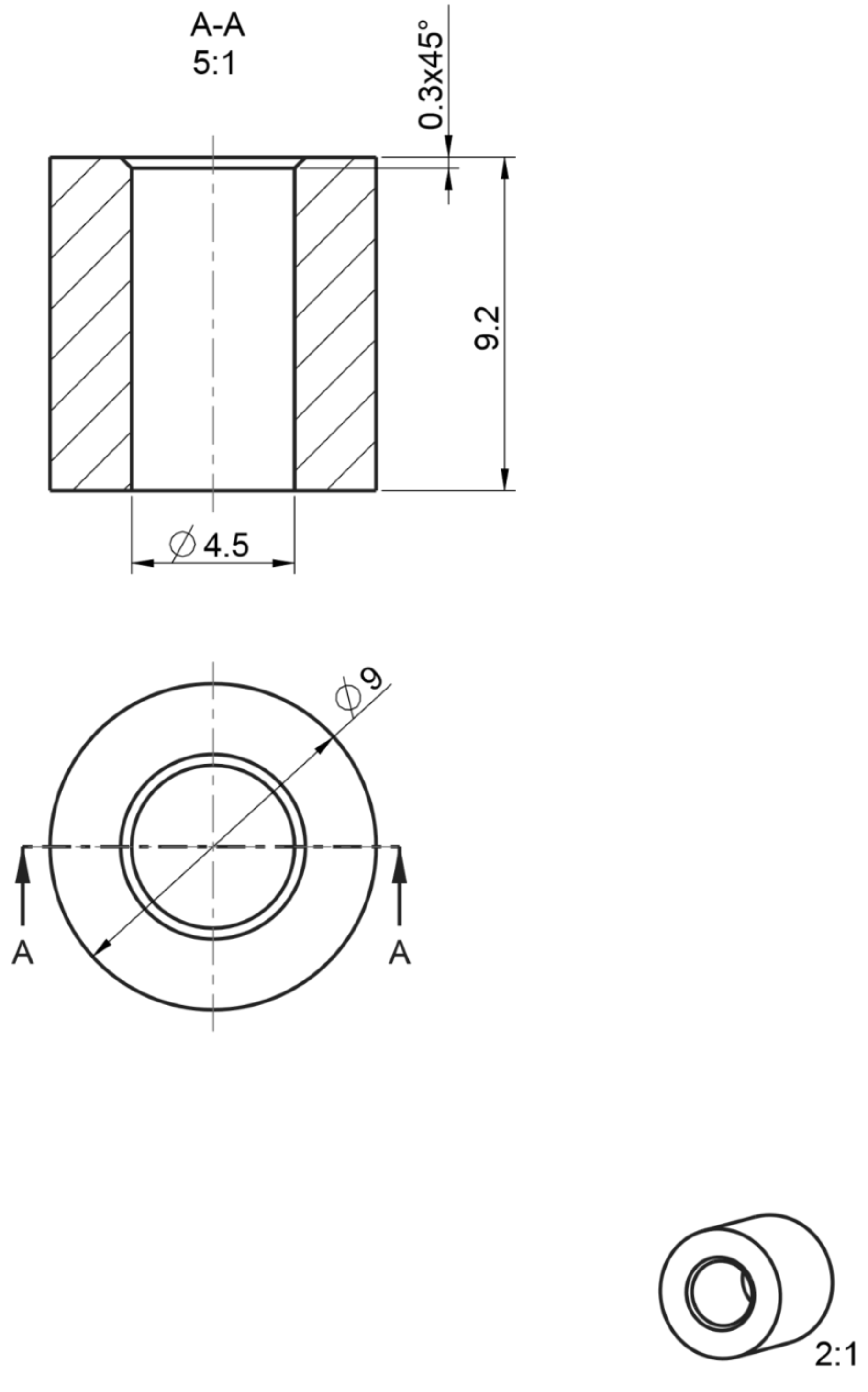
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		2:1	A4

ottobock.	Materialnummer/Materialnumber	Dokumentart/Document type Einzelteilzeichnung/ detail drawing		
Otto Bock HealthCare GmbH Duderstadt	Materialbezeichnung/Materialdescription	Änd./Rev. 0	Datum/Date 20160106	Blatt/Sheet 1/1

Filename: CP_KUGEL_LAGERUNG



Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		5:1	A4

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Duderstadt

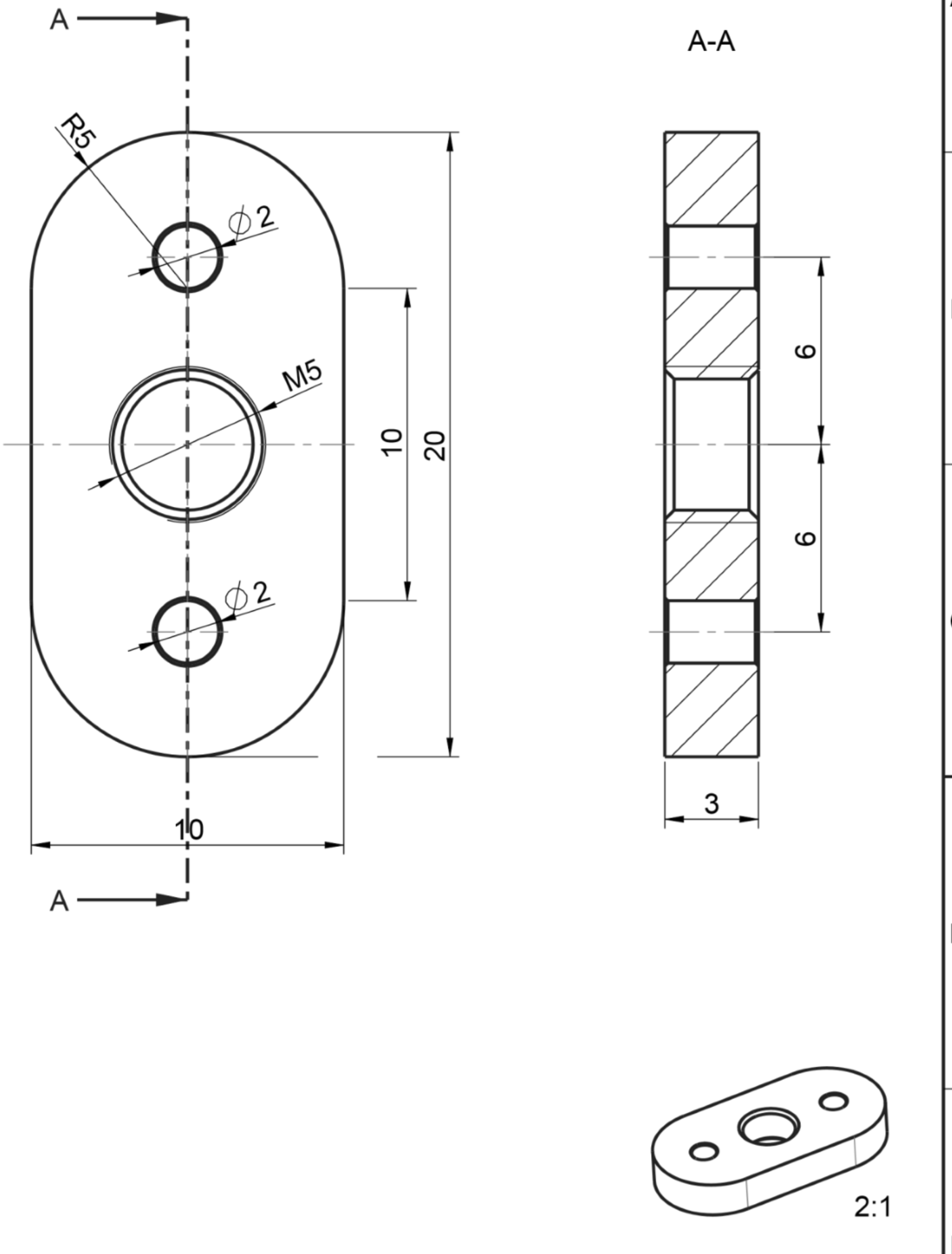
Materialnummer/Materialnumber

Materialbezeichnung/Materialdescription

Dokumentart/Document type
Einzelteilzeichnung/ detail drawing

Änd./Rev.	Datum/Date	Blatt/Sheet
0	20170106	1/1

Filename: CP_LAGERUNGSSTUETZE



Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		5:1	A4

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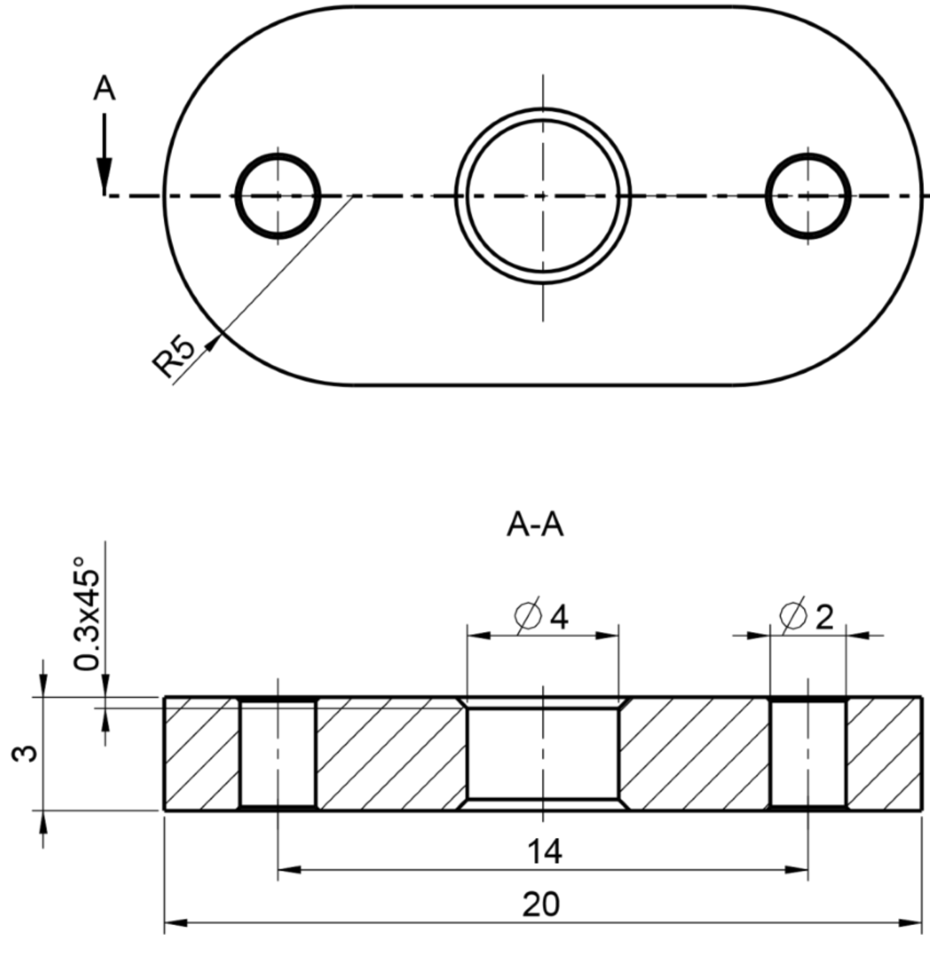
Duderstadt

Materialnummer/Materialnumber	Dokumentart/Document type		
	Einzelteilzeichnung/ detail drawing		
Materialbezeichnung/Materialdescription	**Änd./Rev.**	**Datum/Date**	**Blatt/Sheet**
	0	20170117	1/1

Filename: FEDERHALTERUNG_DAUMEN_DOPPELT



1:1

Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		5:1	A4

ottobock.

Otto Bock HealthCare GmbH
Duderstadt

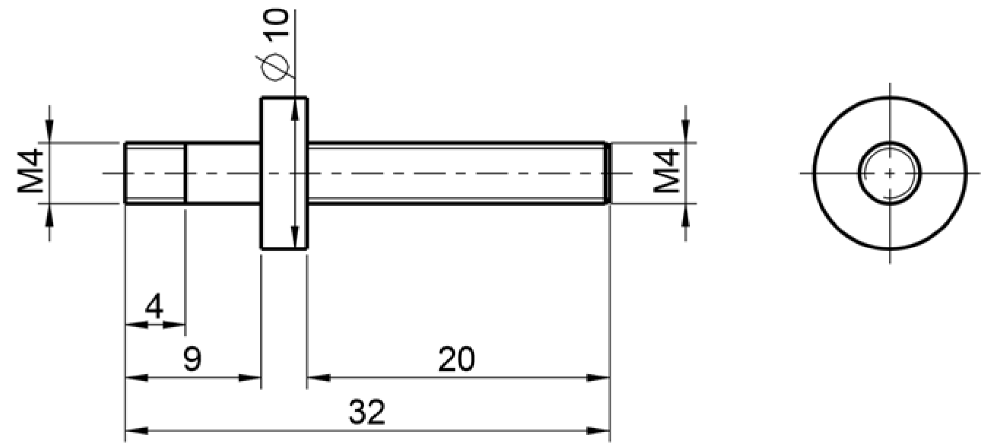
Materialnummer/Materialnumber

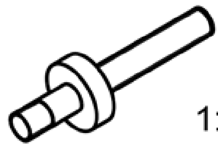
Materialbezeichnung/Materialdescription

Dokumentart/Document type: Einzelteilzeichnung/ detail drawing

Änd./Rev.	Datum/Date	Blatt/Sheet
0	20170112	1/1

Filename: FEDERHALTERUNG_HAND_DOPPELT





1:1

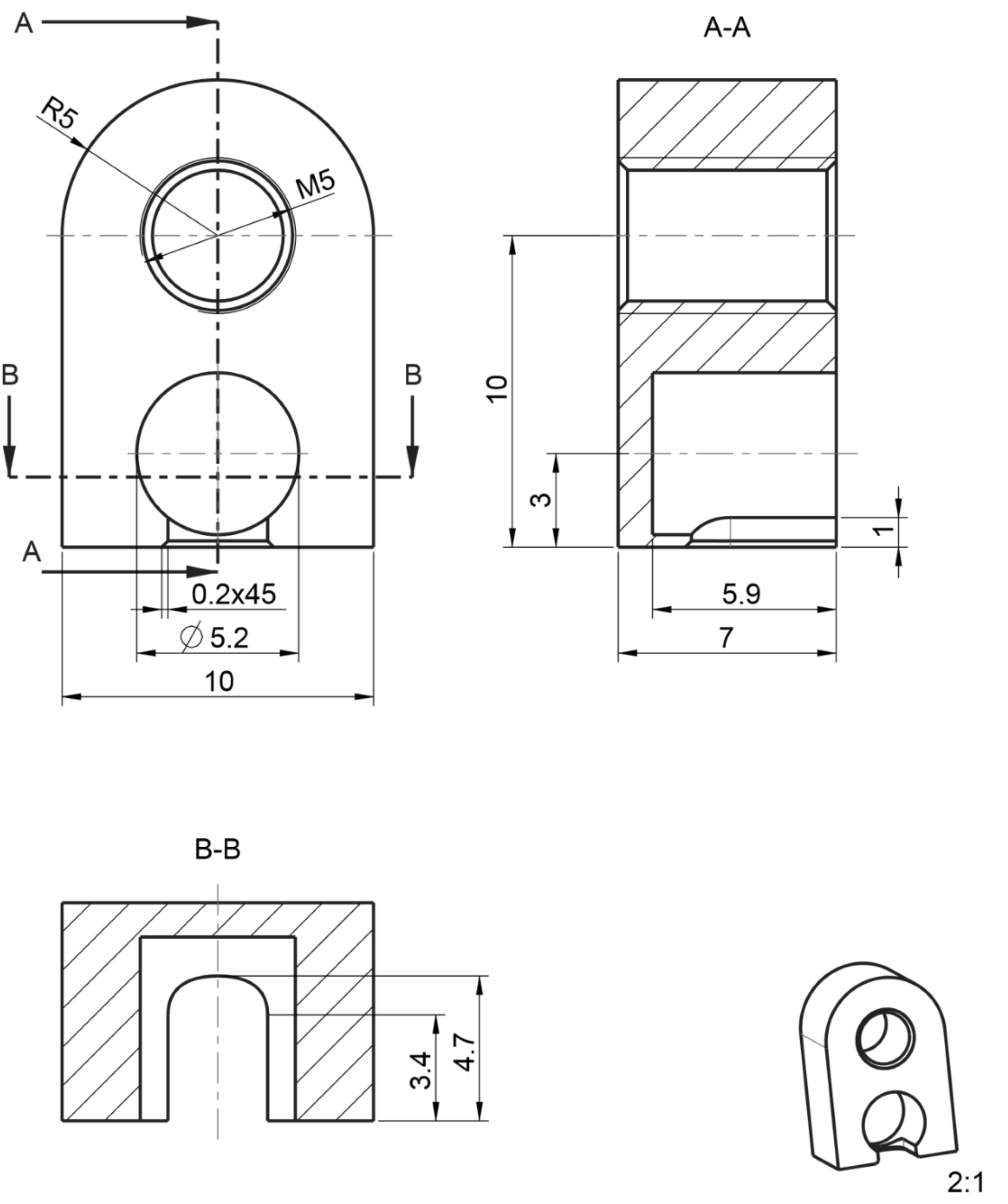
Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		2:1	A4

ottobock.	Materialnummer/Materialnumber	Dokumentart/Document type Einzelteilzeichnung/ detail drawing		
Otto Bock HealthCare GmbH Duderstadt	Materialbezeichnung/Materialdescription	Änd./Rev. 0	Datum/Date 20170106	Blatt/Sheet 1/1

Filename: STIFT_FEDERHALTERUNG_HAND_EIN



Pos.	Materialnummer/ Materialnumber	Materialkurztext/ Materialdescription	Menge/ qty	ME/ Unit	Werkstoff/ Material spec.

Schutzvermerk/Copyright	Allgemeintoleranz/General tolerance	Oberflächenbeschaffenheit/Surface texture	Werkstückkanten/Edges
DIN ISO 16016	DIN ISO 2768-mK	DIN EN ISO 1302	DIN ISO 13715

Gezeichnet/Drawn by	Konstrukteur/Constr. eng.	PV/Product Resp.	Maßstab/Scale	Format/Format
Schulze	Bierbaum		5:1	A4

ottobock.

Otto Bock HealthCare GmbH
Duderstadt

Materialnummer/Materialnumber	Dokumentart/Document type		
	Einzelteilzeichnung/ detail drawing		
Materialbezeichnung/Materialdescription	**Änd./Rev.**	**Datum/Date**	**Blatt/Sheet**
	0	20170106	1/1

Filename: CP_SEILBEFESTIGUNG_DAUMEN_

B

Data Sheets of Springs

Datenblatt Zugfeder : Z-111I

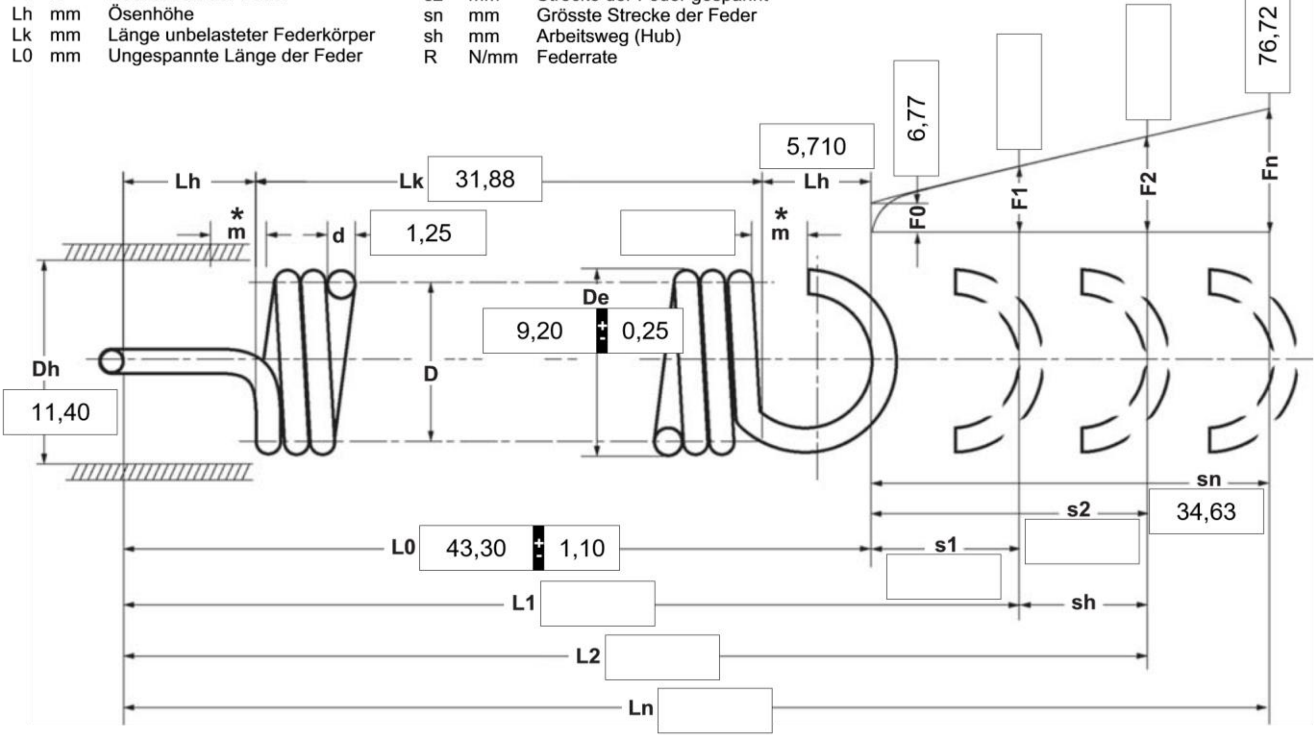
GUTEKUNST FEDERN

02.2017

d	mm	Drahtdurchmesser	L1	mm	Länge der Feder vorgespannt
D	mm	Mittlerer Windungsdurchmesser	L2	mm	Länge der Feder gespannt
De	mm	Äußerer Windungsdurchmesser	Ln	mm	Grösste Länge der Feder
Dh	mm	Kleinster Hülsendurchmesser	m	mm	Ösenöffnungsweite der Öse
F0	N	Innere Vorspannkraft	n	St.	Anzahl der federnden Windungen
F1	N	Kraft der Feder vorgespannt	nt	St.	Anzahl der Gesamtwindungen
F2	N	Kraft der Feder gespannt	s1	mm	Strecke der Feder vorgespannt
Fn	N	Höchstkraft der Feder	s2	mm	Strecke der Feder gespannt
Lh	mm	Ösenhöhe	sn	mm	Grösste Strecke der Feder
Lk	mm	Länge unbelasteter Federkörper	sh	mm	Arbeitsweg (Hub)
L0	mm	Ungespannte Länge der Feder	R	N/mm	Federrate

Gewicht g Gewicht der einzelnen Feder

*Die Ösen haben lagermäßig keine Öffnung (m = 0,00). Eine Ösenöffnung können wir jedoch bei Bedarf kurzfristig aufschneiden.



n | nt | R 2,020 | Gewicht 6,360

Federprüfung nach DIN ISO 2859/1 Prüfniveau II

1 Windungsrichtung

☐ links ☒ rechts

2 Ösenform und Ösenstellung

Ösenform

1/1 deutsche Öse

Ösen gegeneinander versetzt

um 180,0 ± 27,0 Grad

(Im Sinne der Rechtsschraube)

3 Arbeitsweg sh mm

4 Lastspielzahl N

5 Lastspielfrequenz n /

6 Arbeitstemperatur °C

7 Werkstoff

EN 10270-1

8 Draht- oder Staboberfläche

☒ gezogen ☐ gewalzt ☐ spanend bearbeitet

9 Oberflächenschutz

10 Toleranzen nach DIN 2097

Gütegrad	De,Di,D	L0	F0-Fn	Ösen	Drahtstärke d nach DIN 2076
1	☐	☐	☐	☐	
2	☒	☒	☒	☒	
3	☐	☐	☐	☐	☒

11 Fertigungsausgleich **durch**

Eine Federkraft, zugehörige Länge der gespannten Feder und L0	F0, D	☒
Eine Federkraft, zugehörige Länge der gespannten Feder und F0	L0, n, d	☐
	L0, D	☐
Zwei Federkräfte, die zugehörigen Längen der gespannten Feder	L0, n, d	☐
	F0,D	☐

Staffelpreise

Mengenstaffel	Einzelpreis [EUR]
1	2,7700 €
7	1,6900 €
17	0,8600 €
37	0,5300 €
75	0,3700 €
125	0,3432 €
175	0,3345 €
250	0,3312 €
350	0,3198 €
450	0,3139 €

Bemerkungen

Gutekunst + Co.KG Federnfabriken · Carl-Zeiss-Straße 15 · D-72555 Metzingen

Verkauf (+49) 07123 / 960-192 · Individuelle Federn (+49) 07123 / 960-193 · Zentrale (+49) 07123 / 960-0

Telefax (+49) 07123 / 960-195 · E-mail: verkauf@gutekunst-co.com

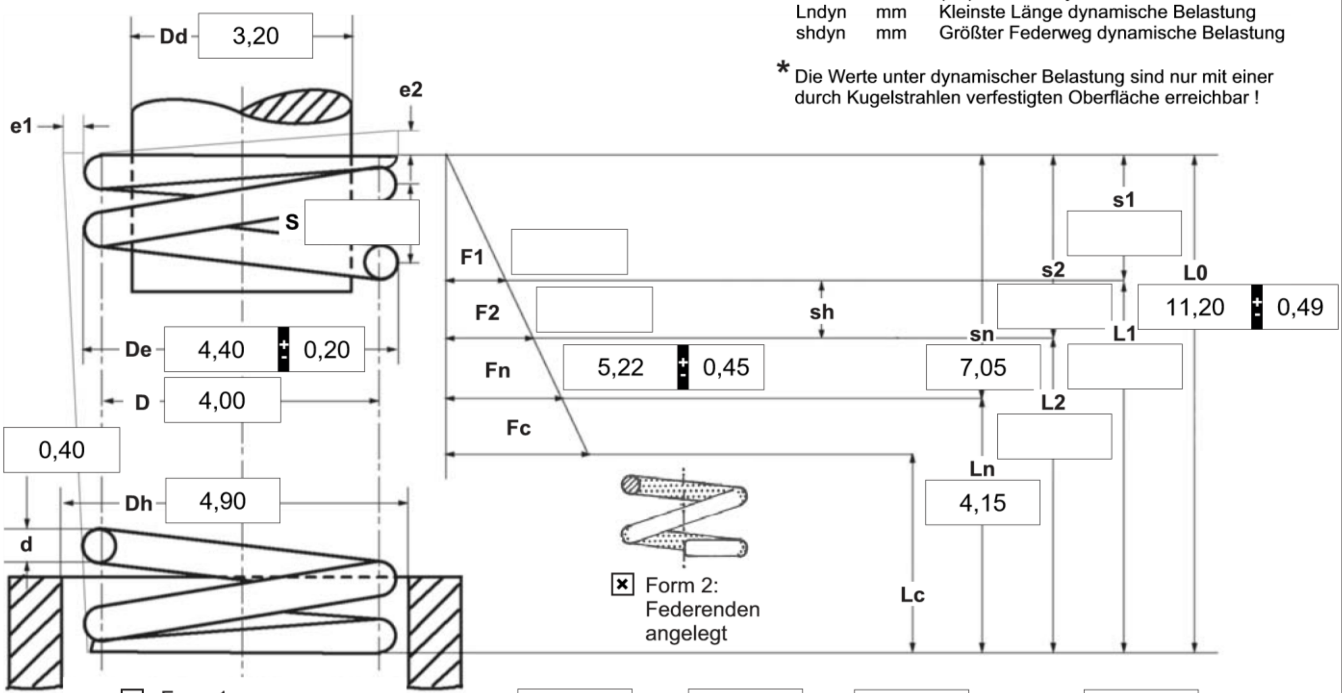
Datenblatt Druckfeder : D-049

GUTEKUNST FEDERN

02.2017

d	mm	Drahtdurchmesser	Fn	N	Höchstkraft der Feder	nt	St.	Anzahl der Gesamtwindungen
D	mm	Mittlerer Windungsdurchmesser	Fc	N	Theo. Federkraft bei Blocklänge	R	N/mm	Federrate
Dd	mm	Dorndurchmesser	L0	mm	Ungespannte Länge der Feder	S	mm	Steigung der Federn
De	mm	Äußerer Windungsdurchmesser	L1	mm	Länge der Feder vorgespannt	s1	mm	Strecke der Feder vorgespannt
Dh	mm	Hülsendurchmesser	L2	mm	Länge der Feder gespannt	s2	mm	Strecke der Feder gespannt
e1	mm	Abweichung von Mantellinie	Lk	mm	Knicklänge	sh	mm	Arbeitsweg (Hub)
e2	mm	Abweichung von Parallelität	Ln	mm	Kleinste Länge der Feder	sn	mm	Grösste Strecke der Feder
F1	N	Kraft der Feder vorgespannt	Lc	mm	Blocklänge	Gewicht	g	Gewicht der einzelnen Feder
F2	N	Kraft der Feder gespannt	n	St.	Anzahl federnden Windungen			
						Fndyn	N	Dynamische Höchstkraft
						Fndtol	N	(+/-) Toleranz dynamische Höchstkraft
						Lndyn	mm	Kleinste Länge dynamische Belastung
						shdyn	mm	Größter Federweg dynamische Belastung

* Die Werte unter dynamischer Belastung sind nur mit einer durch Kugelstrahlen verfestigten Oberfläche erreichbar !



n 5,50 **nt** **R** 0,741 **Gewicht** 0,094

Federprüfung nach DIN ISO 2859/1 Prüfniveau II

1 Windungsrichtung

☐ links ☒ rechts

2 Dynamische Beanspruchung *

Fndyn	5,02
Fndtol	0,44
Lndyn	4,43
shdyn	2,58

3 Arbeitsweg sh mm

4 Lastspielzahl N

5 Lastspielfrequenz n /

6 Arbeitstemperatur °C

7 Führung und Lagerung DIN EN 13906-1

☐ Dorn ☐ Hülse

Knicklänge **Lk** bei Lagerungsbeiwert

v=0,5 / Bild 5 0,00 mm

8 Werkstoff

EN 10270-1

9 Draht- oder Staboberfläche

☒ gezogen ☐ gewalzt ☐ spanend bearbeitet

10 Federn entgratet ☐ innen ☐ außen

11 Oberflächenschutz ☐ kugelgestrahlt

12 Toleranzen nach DIN EN 15800

Gütegrad	De,Di,D	L0	F1,F2	e1,e2	Drahtstärke d nach DIN 2076
1	☐	☐	☐	☐	
2	☒	☒	☒	☒	
3	☐	☐	☐	☐	☒

13 Fertigungsausgleich **durch**

Eine Federkraft mit zugehöriger Länge	L0	☐
Eine Federkraft mit zugehöriger Länge und L0	n, d	☒
	n, De, Di	☐
Zwei Federkräfte mit zugehörigen Längen	L0, n, d	☐
	L0,n,De,Di	☐

14 Federn setzen

Alle Federn, die nach ihrer Baugröße zum Setzverhalten neigen, sind vorgesetzt.

Staffelpreise

Mengenstaffel	Einzelpreis [EUR]
1	2,5800 €
7	1,5400 €
17	0,6600 €
37	0,3800 €
75	0,1800 €
125	0,1473 €
175	0,1109 €
250	0,0887 €
350	0,0665 €
450	0,0609 €

Bemerkungen

Gutekunst + Co.KG Federnfabriken · Carl-Zeiss-Straße 15 · D-72555 Metzingen

Verkauf (+49) 07123 / 960-192 · Individuelle Federn (+49) 07123 / 960-193 · Zentrale (+49) 07123 / 960-0

Telefax (+49) 07123 / 960-195 · E-mail: verkauf@gutekunst-co.com